Photography by Malcolm Lockwood

Journeys of a Spacecraft

by John T. Gosling, Daniel N. Baker, and Edward W. Hones, Jr.

With an assist from the moon, a spacecraft called ISEE-3 traveled far out along the nightside tail of our earth's magnetic field. There it discovered, among other things, huge ionic plasmoids breaking off from the earth's magnetosphere and hurtling out into space.

The earth's magnetic field acts in many ways like a buffer between us and space. Over and around this field flows the solar wind, a dilute but persistent stream of protons, electrons, and other ions. This flow of charge, with its associated weak magnetic field, distorts the earth's own field, compressing it on the dayside and stretching it out on the nightside of the planet into a long tail much like that of a comet. The resulting field is called the magnetosphere.

How static is this shield? Does the solar wind flow by passively or does it deposit mass and energy within the magnetosphere that must eventually be released in sudden, dramatic bursts? The auroral disturbances known as the northern and southern lights have always been evidence for the latter point of view. But how extensive are the auroral disturbances? Does our magnetosphere dance with invisible storms that reach far out into space?

This aurora, the result of an injection of solar wind plasma into the upper atmosphere, displays the greenish color of an emission from excited oxygen at a wavelength of 5577 angstroms.

One model pictures the magnetosphere to be something like a drippy faucet (Fig. 1). Solar wind plasma seeps into the magnetosphere all along its boundary, accumulating in the tail until a portion breaks off like a swollen drop of water from a faucet. This model requires the operation of a process called *magnetic reconnection* in which different sets of field lines come together, breaking and reconnecting in new configurations. Reconnection permits the transfer of mass and energy from the solar wind into the magnetosphere, causing it to swell and distort, and is also responsible for the pinching off of a portion of the distended geomagnetic field.

How could this or other models be tested? Satellites in the near-earth tail have collected many useful data concerning magnetospheric processes, but, in one sense, the instruments aboard these satellites may have been blinded by the very processes they were trying to measure. It is as if the firing of a cannon was being studied by sitting at the point of the initial explosion! Data needed to be collected further out—where one could actually see the "cannon balls" hurtling by.

The possibility of obtaining such data was realized when orbits were discovered for the ISEE-3 spacecraft (the third in a series of International Sun-Earth Explorers) that used the moon's gravity to take it on several journeys down the geomagnetic tail. These orbits carried the spacecraft to distances far beyond the orbit of the moon into previously unexplored regions of the magnetosphere. Because ISEE-3 carried a Los Alamos instrument designed to measure electron velocity distributions in space, the data collected on these journeys were able to show that magnetic reconnection plays a critical role in the behavior of our magnetosphere.

It is now felt that the interaction between the solar wind and the magnetosphere does indeed resemble a drippy faucet. The solar wind injects plasma into our magnetosphere along reconnected field lines. When a critical amount of plasma and energy have built up within the tail, field lines in the central portion of the tail pinch off, again by the process of magnetic reconnection, and a bundle of plasma and field lines called a plasmoid suddenly forms and shoots out into interplanetary space. Plasma and field lines inside the breakage point snap back toward the earth, injecting charged particles into our atmosphere and causing an auroral disturbance. Thus, auroral disturbances are only one aspect of a much more widespread disturbance involving the entire magnetosphere.

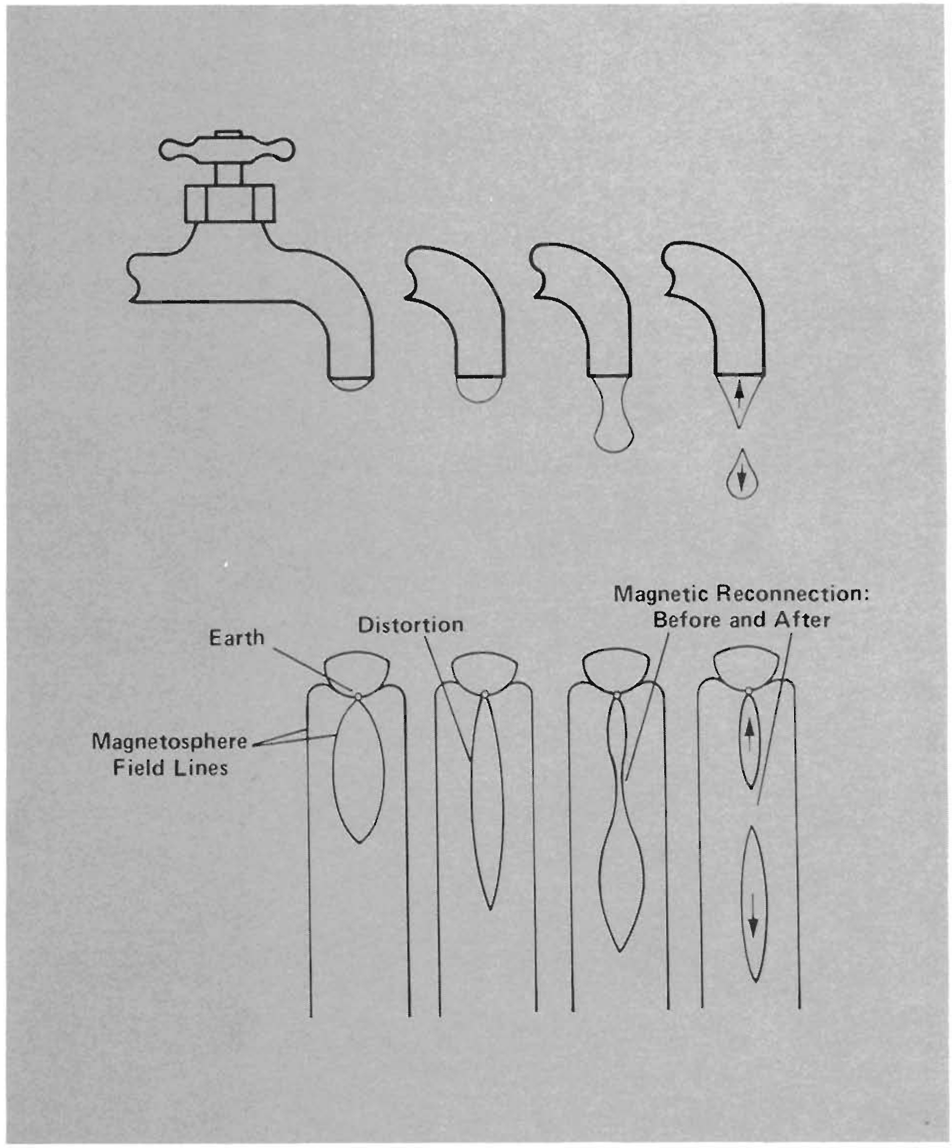


Fig. 1. The drippy-faucet model of the magnetosphere in which (lower series) solar wind plasma is added to the magnetosphere, causing part of it to swell and distort until magnetic reconnection of field lines allows one portion to break away and another portion to spring back toward the earth.

Models of the Magnetosphere

The earth's magnetic field originates from electric currents flowing within the liquid metallic core of the earth. Before the solar wind was taken into account, this field was pictured as an undistorted magnetic dipole (part (a) of Fig. 2).

The first modification to the dipole model occurred after the existence of the solar wind was suggested (see "The Solar Wind") but before satellites had begun to explore the distant reaches of space around the earth and record the properties of the solar wind. Many scientists thought that the continuous flow of the solar wind plasma might force the earth's magnetic field into the shape depicted in part (b) of Fig. 2. Both this model, proposed by Francis Johnson in 1960, and the dipole model are *closed* magnetospheres, that is, ones in which all the field lines leaving one hemisphere of the earth return to the other hemisphere.

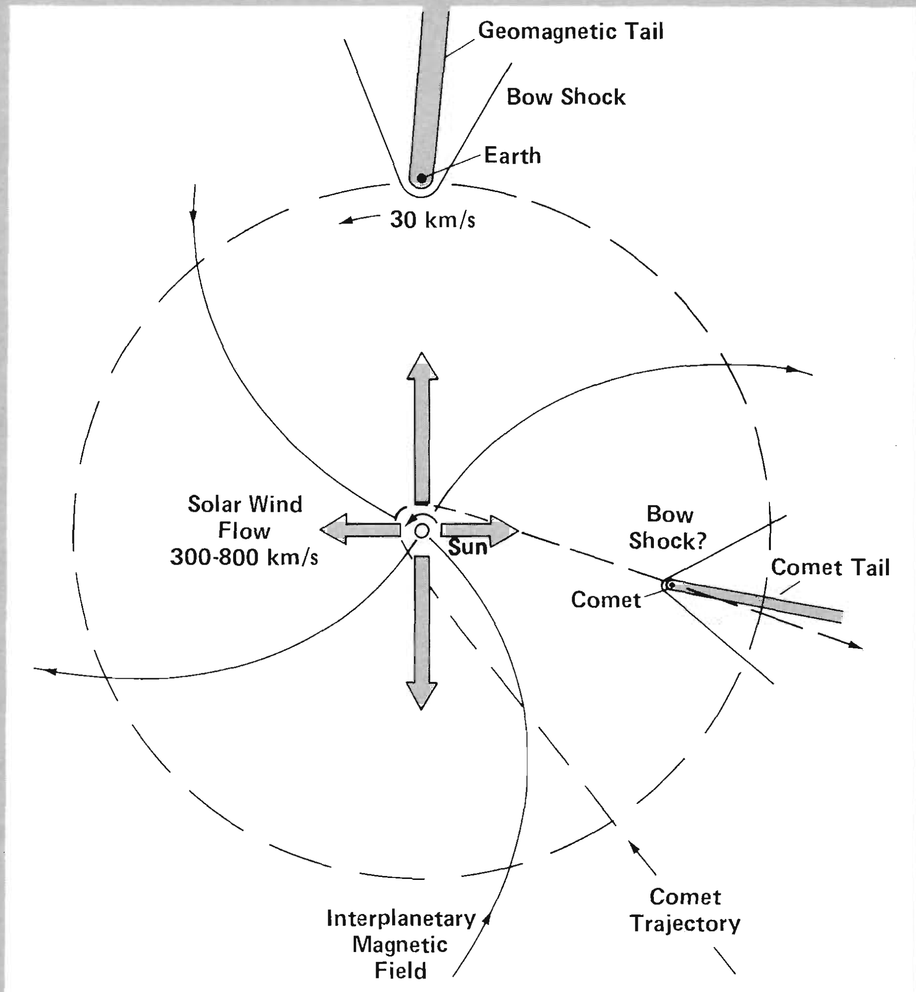
Early in the sixties satellites measured for the first time the magnetic field of the solar wind. In 1961 James Dungey proposed that the interplanetary field lines carried by the solar wind might interconnect with the terrestrial field lines, creating the field geometry sketched in part (c) of Fig. 2. This is an *open* magnetosphere because field lines from high latitudes on the earth do not return to the other hemisphere. Instead, they are connected to the field of the solar wind.

Magnetic Reconnection. The two highlighted regions in part (c) of Fig. 2 are of great interest because they both have fields of opposite polarity that are pushed together. On the dayside (left) the interplanetary and the terrestrial field lines are oppositely directed; on the nightside (right) it is the terrestrial field lines above and below the

The Solar Wind

The sun's outer atmosphere, the corona, has been familiar to man for many centuries as the faint silvery glow surrounding the black disk of the moon during a total eclipse of the sun. Only in recent years, however, has man learned that the corona pervades the entire solar system as a wind of ionized gas, gusting outward from the sun at speeds that vary from 300 to 800 kilometers per second (see figure). This wind is a consequence of the million-degree temperature and the high thermal conductivity of the ionized coronal gas. These conditions produce such a high and extensive thermal pressure that even the enormous gravity of the sun is insufficient to contain the corona as a static, bound atmosphere.

As the solar wind rushes outward, it carries frozen within it a remnant of the sun's magnetic field. If the sun did not rotate, the resulting interplanetary magnetic field would be nearly radial. Solar rotation (once about every twenty-seven days as viewed from the earth) forces the interplanetary field into an Archimedean spiral (when viewed from above as shown in the figure). The polarity of the field, that is, whether it is directed away from or toward the sun, depends on the polarity of the field at the sun where the flow of plasma originates. Because the solar magnetic dipole is generally inclined significantly to the solar equator, the polarity of the solar wind field at earth tends to reverse sign two or more times per solar rotation.



The solar system is filled with a supersonic solar wind blowing nearly radially outward from the sun. Embedded in the flow is a remnant of the solar magnetic field, which, however, is not radial but is bent into an Archimedean spiral by the rotation of the sun. The flow of the solar wind past the earth produces a stretching of the earth's magnetic field into a long, tail-like structure on the nightside and causes a detached bow shock to form on the dayside. This geomagnetic tail is similar in some respects to the ionic tail of a comet, which results from the interaction of the solar wind with gases emitted from the head of the comet.

The major constituents of the solar wind plasma are protons and electrons. Typical solar wind densities measured at the earth are about 10 particles per cubic centimeter, whereas typical field strengths are 5×10^{-5} gauss. By way of comparison, the particle density of the earth's atmosphere at sea level is about 3×10^{19} per cubic centimeter, and the earth's magnetic field strength at the poles is 0.6 gauss. Despite the dilute nature of the solar wind plasma and the weakness of the interplanetary field, the flow of the solar wind determines the overall shape of the earth's magnetosphere. Further, as observations from satellites have shown, the orientation of the interplanetary magnetic field controls the transfer of mass and energy from the solar wind to the magnetosphere, and this transfer is the cause of auroral disturbances and geomagnetic activity. ■

midplane that are oppositely directed. Plasma regions containing such opposed fields become separated by thin layers of intense electric currents called current sheets. Slow quasi-steady flow of plasma toward the current sheet occurs on both sides (large arrows that point at each other in part (c) of Fig. 2 and in Fig. 3). Such flow carries with it opposing magnetic fields.

To balance the inward flow of plasma there must also be an outward flow. Ejection of energized plasma takes place within the current sheet in two narrow wedge-shaped jets (arrows that point away from each other in part (c) of Fig. 2 and in Fig. 3). The vertices of these jets are located at the x-shaped magnetic neutral point. In part (c) of Fig. 2 we see that in the open model of the magnetosphere, outward jetting of plasma at the front of the magnetosphere can link up with inward flow of plasma at the rear. Some terrestrial field lines are broken at the front of the magnetosphere, become connected to interplanetary field lines, are dragged into the tail by the flow of the solar wind, and finally reconnect far down the tail at a distant neutral line. Thus, there is a net flow of plasma and field over both poles of the earth. Reconnection at the rear of the magnetosphere either directs plasma back toward the earth or out into space.

If we watch the fate of the magnetic field lines being carried in by the flow of plasma in Fig. 3, we can understand the origin of the term magnetic reconnection. Field lines such as C_1-C_2 and D_1-D_2 are carried toward the current sheet. When they touch at the magnetic neutral point (the primed lines), they are severed and reconnected. Subsequently, they leave the system in the exit jets as field lines C_1''-D_1'' and C_2''-D_2''.

The plasma motion leads to an electric field that is perpendicular to the plane of the magnetic field lines shown in Fig. 3. The finite resistivity of the plasma near the neutral point prevents the short circuiting of this field.

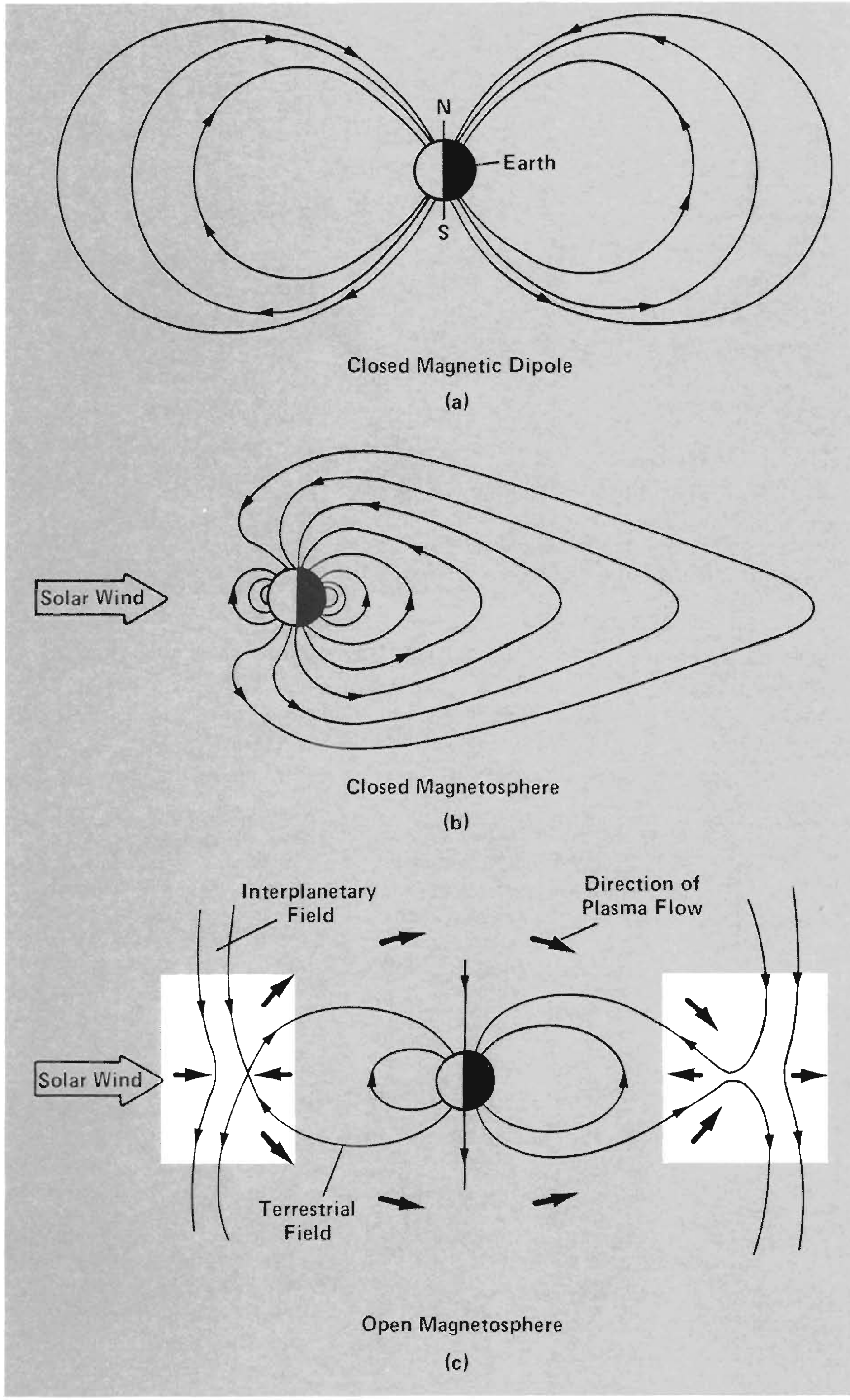


Fig. 2. Three stages in the evolution of our knowledge of the earth's magnetosphere: (a) The original model was a simple, closed magnetic dipole extending into a vacuum. (b) A model in which the solar wind flowed past the earth without the interconnection of interplanetary and terrestrial field lines depicted a distorted magnetosphere, but one that was still closed; that is, all field lines started and ended on the earth, and the solar wind merely flowed around the magnetosphere. (c) An open magnetosphere resulted when the interconnection of the terrestrial field with a weak interplanetary field carried by the solar wind was added to the model. The interconnection of the two sets of field lines allows plasma and energy from the solar wind to move into and through the magnetosphere. (For simplicity the tilt of the earth's axis is not shown.)

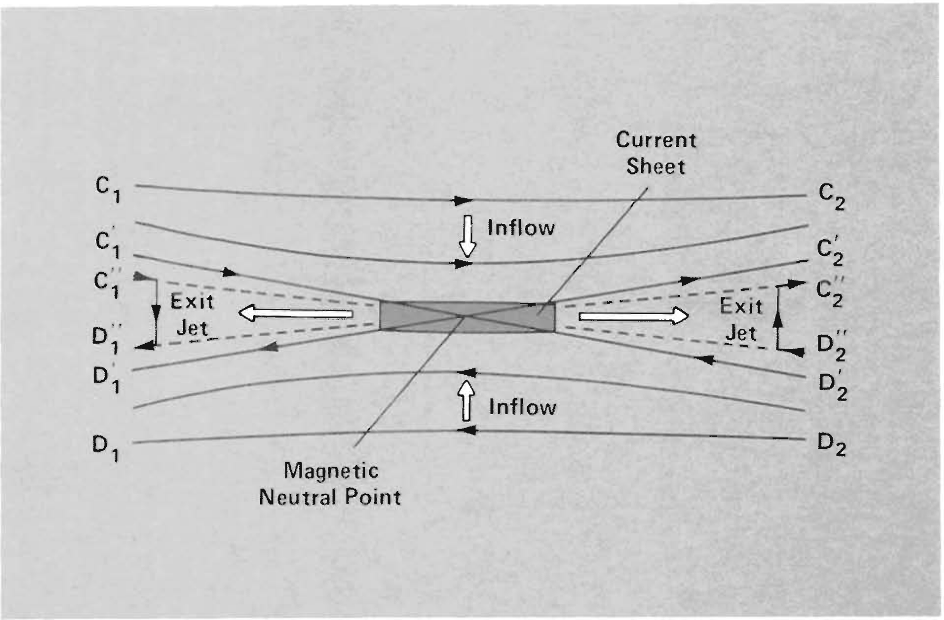


Fig. 3. Magnetic reconnection induced by flow of plasma (arrows). Carrying magnetic field lines of opposite orientation (unprimed) with it, plasma moves slowly from top and bottom toward the neutral point. Here the field lines (primed) break and reconnect. Tension within the reconnected field lines produces fast plasma jets moving to the left and right that carry the reconnected field lines (double primed) with them. (Adapted from a figure on page 75 in Space Science Physics: The Study of Solar-System Plasmas *(National Academy of Sciences, Washington, D.C., 1978).)*

An Incomplete Model of the Magnetosphere. Plasma and magnetic field measurements made by many satellites since 1961 suggest that the magnetosphere is indeed open, substantially in agreement with Dungey's model. However, these data were not decisive about many important details. For example, does solar wind plasma enter only at the front of the magnetosphere or all along its surface? How far down the tail is the distant neutral point? Are auroral disturbances relatively localized events or is the whole magnetosphere affected? What happens far from earth during an energy release? We will first describe what are believed to be the main features of the magnetosphere as pieced together from near-earth observations. Later in the article we will show how measurements far down the tail of our magnetosphere have begun answering these questions by filling out the model with many exciting details.

The very long magnetic tail of the magnetosphere extends more than six million kilometers downstream in the solar wind (Fig. 4), much like the tail of a comet. The transverse cross section of this magnetotail is roughly circular and 250,000 to 350,000 kilometers in diameter. Extending entirely across the magnetic midplane of the tail is a flat *plasma sheet* (seen edge on in Fig. 4). Field lines within the plasma sheet are rooted in opposite hemispheres at the earth; that is, plasma sheet field lines are closed. This region, the plasma sheet, is where much of the solar wind plasma accumulates. The energy extracted from the solar wind and stored in the first 600,000 kilometers of the tail is equivalent to a 1- to 10-megaton bomb, and the mass is several tons.

The electric field generated by the flow of the solar wind past the magnetosphere causes an electric current to move crosswise through the plasma sheet (flowing out and normal to the plane of Fig. 4). The current closes around the circumference of the tail, forming two gigantic solenoids that create the regions of strong magnetic field above and below the plasma sheet. These regions, called *tail lobes*, also contain plasma but generally of a much lower density than that of the plasma sheet. Lobe field lines are open, one end being tied to the earth and the other to the solar wind. This fact allows solar wind plasma to enter the magnetic tail.

Thus, inward flow of plasma appears to be a result of magnetic reconnection. At the front of the magnetosphere, reconnection occurs continuously but at a variable rate. This rate depends on the solar wind flow speed and the degree to which the two fields are antiparallel. The latter condition, in turn, depends on the momentary orientation of the solar wind field, which varies through a full range of orientations (over a period of months the north-south component averages to zero). A southward orientation with interplanetary field lines opposing the direction of the dayside terrestrial field lines (the configuration shown in part (c) of Fig. 2) is thought to result in the greatest rate of plasma accumulation within the magnetosphere.

The surface of the magnetosphere is called the *magnetopause*. Close to but just beneath the magnetopause on lobe field lines is another region of higher plasma density called the *plasma mantle*. This is solar wind plasma that has entered the magnetosphere and is flowing tailward. The cross-tail electric field causes this moving plasma to convect gradually toward the plasma sheet (along the dashed lines in Fig. 4).

At the far right of Fig. 4 is a distant magnetic neutral point where the plasma sheet of closed field lines ends. If reconnection occurs at the front of the magnetosphere, it must also occur here in the tail so that neither the earth nor the solar wind experiences a net gain of magnetic flux. Thus, in the open model we also find a continuous process of reconnection at this distant neutral point. New, closed plasma sheet field lines are being constantly formed here from open lobe field lines, and plasma is ejected into the plasma sheet. In the opposite direction the reconnection process generates unconnected interplanetary field lines that become part of the solar wind as it flows away from the earth.

The picture of the magnetosphere depicted so far uses magnetic reconnection to move solar wind plasma into the magnetosphere where it then drifts tailward toward the plasma sheet. But this process results in a net gain of mass and energy in the magnetosphere that must eventually be released. Will the release be a continuous, steady-state bleeding of plasma from the magnetosphere, or will it be a sporadic release?

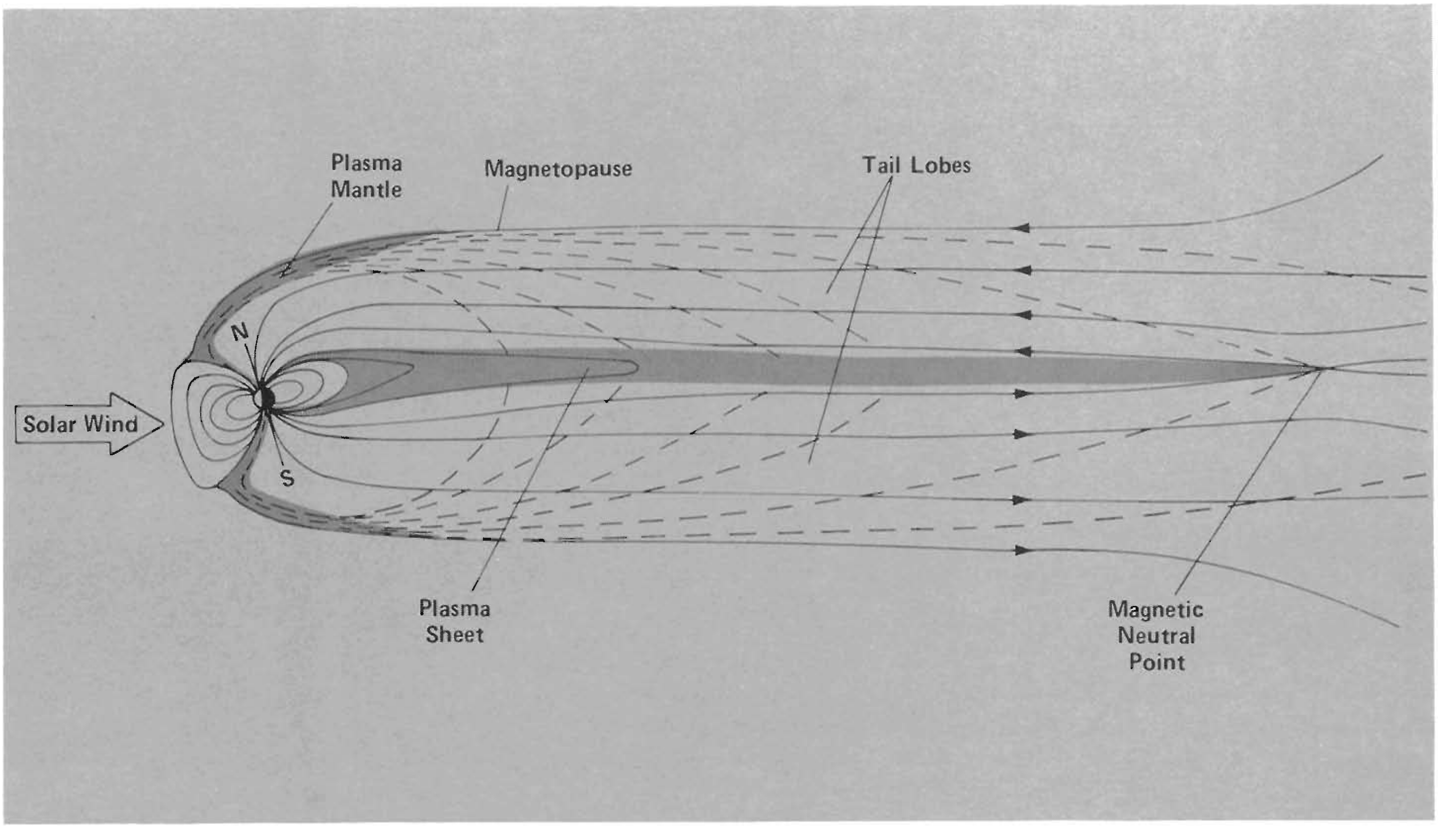


Fig. 4. A modern view of the magnetosphere. Solar wind plasma crosses the magnetopause (the surface of the magnetosphere) on reconnected field lines on the dayside to form the plasma mantle and drifts along the dashed lines through the plasma-poor tail lobes to populate the flattened, horizontal plasma sheet.

Energy Release. Evidence of one kind of sporadic energy release can be found by observing comets. A comet's tail is the result of the comet's interaction with the solar wind, probably similar in some respects to the interaction of the earth's magnetosphere with the solar wind. In fact, the existence of the solar wind was first inferred in the 1950s from an analysis of the ionic tails of comets. (In a sense, studies of the geomagnetic tail and comet tails are complementary. We can directly observe a variety of physical processes in the geomagnetic tail *in situ* with satellites but must infer its overall structure from single point measurements. On the other hand, we can directly observe optically the overall structure of a comet tail but as yet have not had an opportunity to make *in situ* measurements. In September 1985, ISEE-3, renamed ICE, will pass through the tail of a comet to provide the first such direct measurements.)

Dramatic evidence for the manner in which comets can lose energy accumulated from the solar wind is provided by Fig. 5, which shows the tail of a comet breaking off, severed, it is thought, by magnetic reconnection. Here the reconnection occurs sporadically. Does a similar loss mechanism take place in the earth's magnetosphere? Does magnetic reconnection of previously closed field lines occur deep in the plasma sheet? Is such a process responsible for auroral disturbances?

The term *auroral substorm* was coined by Syun Akasofu, who found that for a ground-based observer the auroras in the local midnight sector at high geomagnetic latitudes often brighten dramatically and spread rapidly poleward over a period of from thirty minutes to an hour. The process is repeated at irregular intervals, averaging once every few hours. Figure 6, an ultraviolet image of the earth and its upper atmosphere taken from a satellite about 25,000 kilometers above the north pole, shows an example of such a disturbance on a global scale.

During the past decade instruments on satellites orbiting to distances of about 200,000 kilometers into the magnetotail have returned plasma and magnetic field data

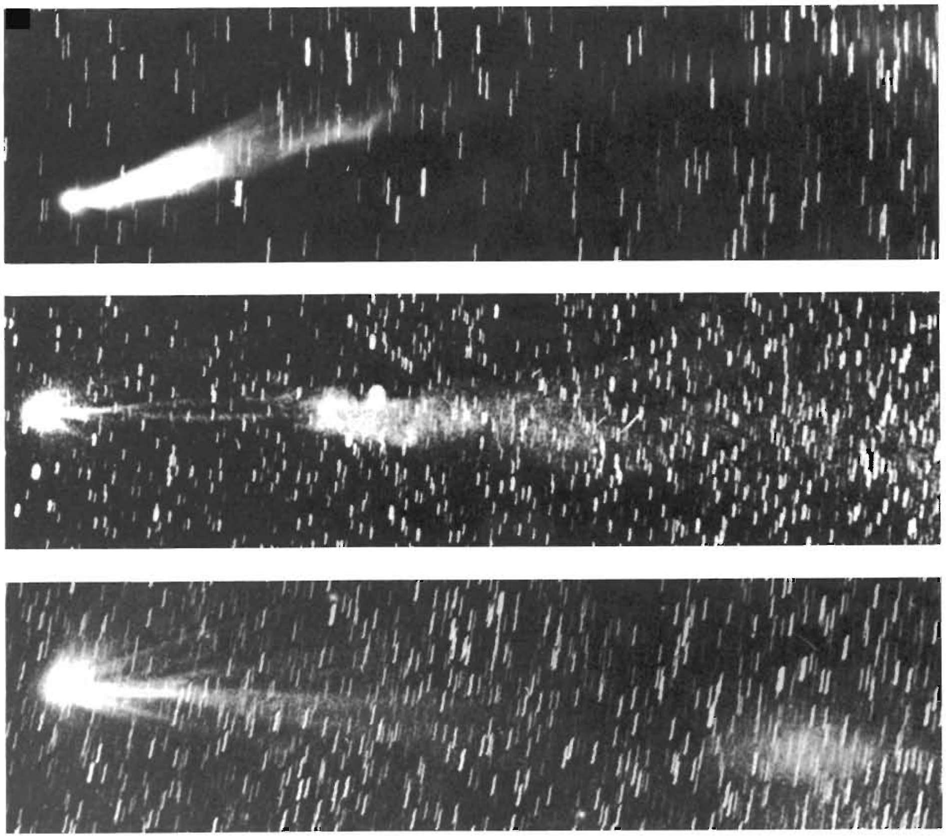
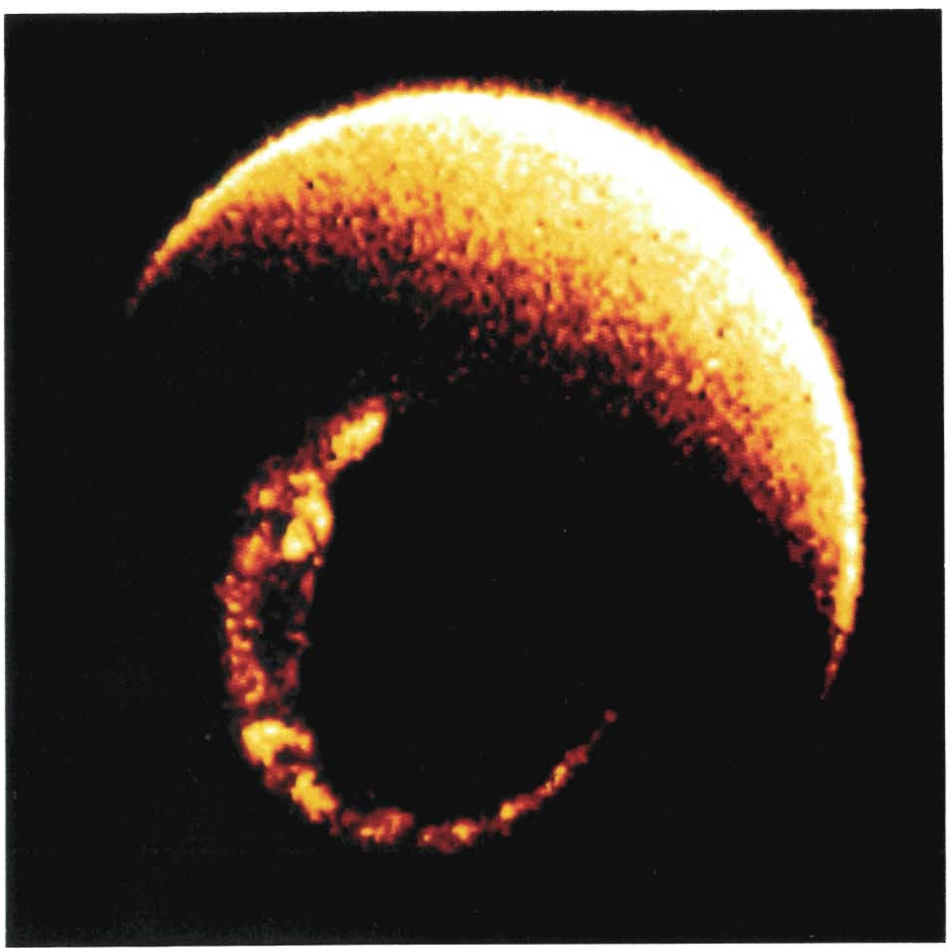


Fig. 5. Photograph (courtesy of Yerkes Observatory) of the comet Morehouse on (top to bottom) September 30, October 1, and October 2, 1908, showing the disconnection and drifting away of a portion of the comet's plasma tail.



relevant to understanding the cause of these auroral substorms. These data, recorded at positions relatively close to the earth (compared to the greater than six-million-kilometer length of the magnetotail), suggested that at about the same time an auroral substorm begins, a longitudinal sector of the tail's plasma sheet is severed by magnetic reconnection (Fig. 7). The plasma sheet field lines earthward of the reconnection point contract rapidly, driving plasma down field lines into the polar atmosphere. This process causes the auroral disturbance seen from the surface of the earth. Thus, in this model, the northern and southern lights are a by-product of the magnetosphere's sudden loss of plasma and energy.

The model also predicts that in the opposite direction a severed plasmoid of closed field lines forms and flows tailward to join the solar wind far downstream. To confirm this idea and to determine just how open the magnetosphere is—in short, to flesh out the model—we needed data from instruments deep in the tail.

Fig. 6. The aurora. This color-coded ultraviolet image of the earth was taken with University of Iowa instrumentation aboard NASA's Dynamic Explorer satellite from a point 3.27 earth radii above the north polar cap. The broad crescent is a portion of the sunlit hemisphere; the narrow crescent is an aurora on the nightside of the earth. Principal contributions are from emission lines of atomic oxygen with wavelengths of about 130.4 and 135.6 nanometers. Reconnection in the plasma sheet of the geomagnetic tail causes plasma to jet both earthward and tailward. The earthward jetting plasma causes an auroral disturbance as it impacts the earth's upper atmosphere.

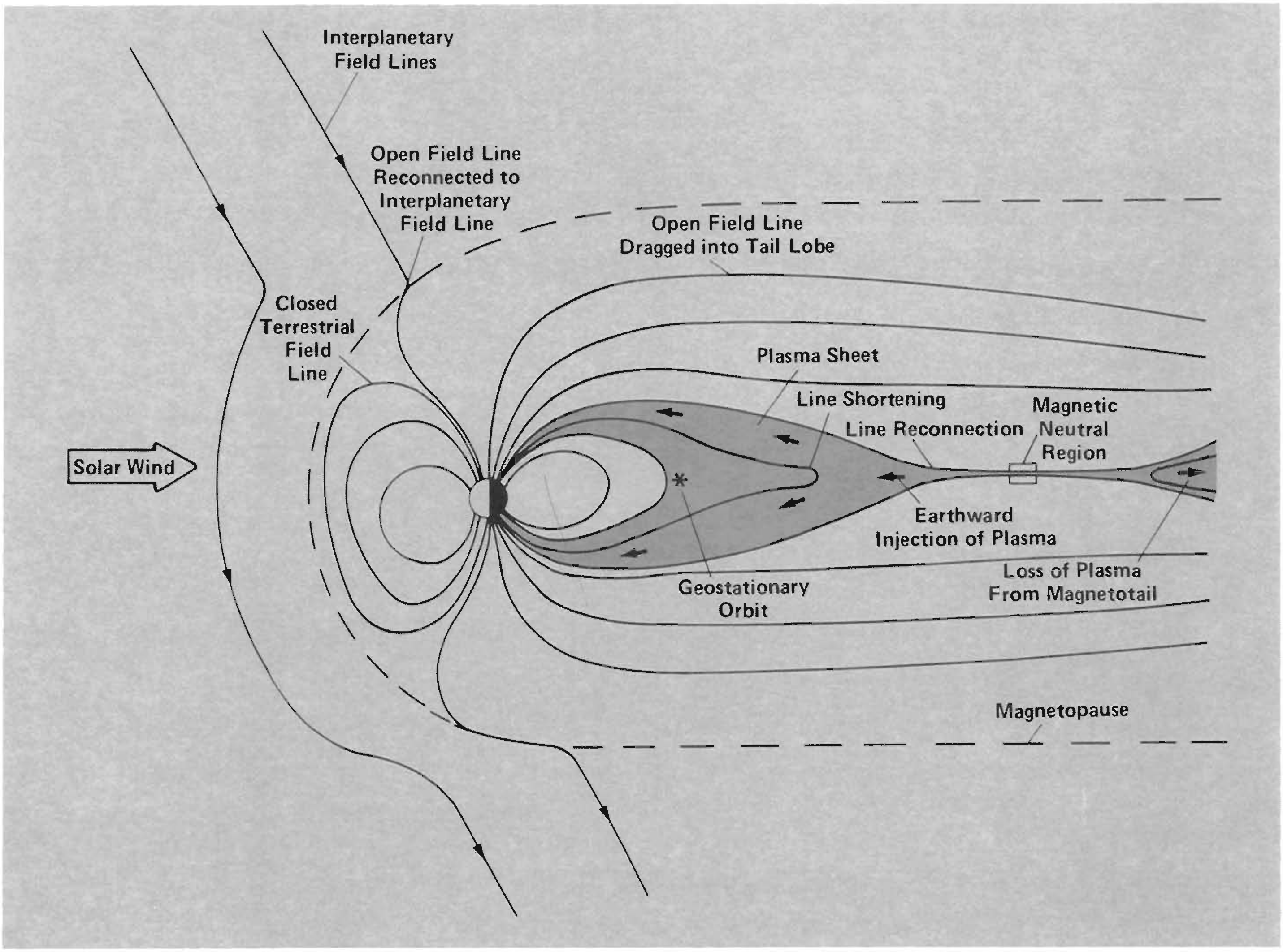


Fig. 7. Features of magnetic substorms inferred from many years of near-earth observations. Interplanetary field lines interconnect with terrestrial field lines near the front of the magnetosphere and are dragged back to form the tail lobes, carrying plasma and energy with them. Far down the tail (off the figure to the right), lobe field lines reconnect to form the plasma sheet. When the midsection of the plasma sheet becomes thin enough (due to increased magnetic pressure from the tail lobes), field lines reconnect there also, forming the magnetic neutral region shown. The release of energy that results from the reconnection heats and accelerates magnetotail plasma, driving part of the plasma back along field lines into the earth's atmosphere at the poles. Another blob of plasma is driven to the right, flowing at great velocity down the tail. Before ISEE-3's journeys into the magnetotail, we could only speculate about what occurred beyond the right-hand side of the figure.

ISEE-3's Journeys

In August 1978 NASA launched ISEE-3, the last of a triad of spacecraft designed to study the solar wind and its interaction with the earth's magnetosphere. ISEE-3 was in orbit for four years about the sunward Lagrangian point approximately 1,400,000 kilometers (220 earth radii) upstream from the earth where it provided many useful measurements of the solar wind. However, Robert Farquhar at NASA discovered unique three-body orbits involving the moon, the earth, and the spacecraft that were ideally suited for exploring the deep geomagnetic tail. So in the summer of 1982, ISEE-3 was moved out of its original orbit into a lunar-controlled orbit for deep tail exploration.

The spacecraft first crossed the tail in October 1982, still moderately close to the earth (400,000 to 600,000 kilometers). Then in December 1982 it started down the tail, reaching its apogee (or turnaround point) almost 1,500,000 kilometers into the tail on February 8, 1983 (Fig. 8). A shorter journey in April 1983 took it back down the tail to about the 500,000-kilometer point. These and several other journeys since then have allowed us to sample the tail's structure in the previously unexplored region from 400,000 to almost 1,500,000 kilometers (60 to 230 earth radii).

Plasma Data from the Distant Tail. Figure 9 is a photograph of the apparatus aboard ISEE-3 designed (under the leadership of Samuel J. Bame) to measure the velocity distributions of electrons in space. During the 3-second spin of the spacecraft, the instrument counts the number of electrons in fifteen contiguous energy bins (from below 10 to above 1 thousand electron volts (eV)) at each of 16 azimuthal angles spaced at intervals of about 23 degrees. This allows a relatively quick "snapshot" of the electron

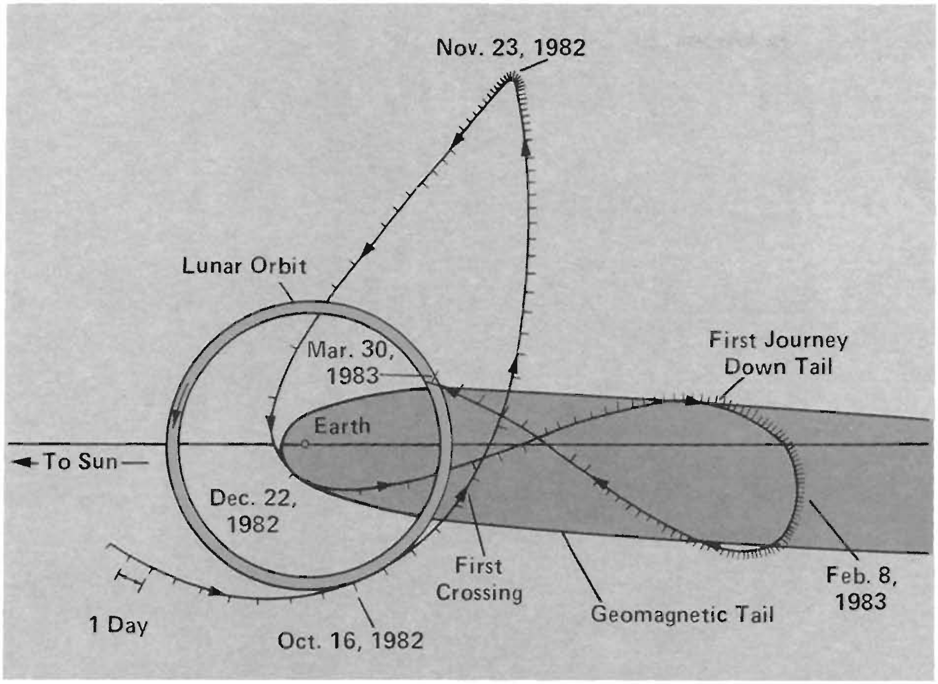


Fig. 8. The initial journeys of ISEE-3 across and down the magnetotail. The orbits, as seen from earth, are projected onto the ecliptic plane; each tic mark corresponds to one day. Lunar swing-bys were used judiciously to set up several orbits that allowed ISEE-3 to remain for long periods in the distant tail at distances up to 1,500,000 kilometers, or 230 earth radii.

Fig. 9. Equipment carried by ISEE-3 for the Los Alamos plasma experiment. The instrument has a 135-degree spherical-section electrostatic analyzer (behind the upper opening) followed by a secondary emitter system (the concave disk in the upper opening) and a 20-stage focused mesh electron multiplier (held by Samuel Bame). The number of electrons in each of fifteen contiguous energy bins from 8.5 eV to 1.14 keV is counted by varying the voltage stepwise on the analyzer plates. From these data the density, flow speed, temperature, and heat flux of plasma electrons everywhere along the spacecraft's orbit can be determined.

thermal distribution surrounding the spacecraft. The measurement is usually repeated every 84 seconds, although repetition rates of 12 seconds are within the capabilities of both the instrument and the spacecraft telemetry and are used on occasion.

Figure 10 shows how the raw data are displayed as a color spectrogram for initial analysis. The four panels give electron energy spectra averaged over the quadrants centered, respectively, on the spacecraft's noon, dusk, midnight, and dawn viewing directions. In each panel electron energy increases logarithmically from bottom to top and time progresses from left to right over a 12-hour span. The color represents a logarithmic scale of counts, ranging from dark blue for very few (10^4) to red for very many (10^4).

The spectra of Fig. 10 were taken on January 24, 1983, when the spacecraft was close to apogee. The variability evident in the figure is typical of data from deep in the tail and includes various crossings of boundaries between the major regions characterizing this part of the magnetosphere. For example, the first two major spectral changes are associated with a crossing that starts outside the tail, passes through the magnetopause into the southern tail lobe (at 1:10 universal time (UT)), and then passes from the lobe into the plasma sheet (at 4:20 UT). Some additional crossings of the magnetopause are also labeled in the figure.

The large number of such transitions between various regions of the distant tail is, at first, surprising because at apogee the spacecraft is nearly stationary relative to the sun-earth line (Fig. 8). Some of the crossings are caused by the daily wobble of the geomagnetic dipole relative to a fixed direction in space and by flapping of the tail in response to changes in the direction of the solar wind. A directional shift of 1 degree at the earth will be seen close to the spacecraft's apogee as a displacement of the entire tail by 3.5 earth radii. Solar wind shifts of this magnitude and even larger are common. However, as we will see, some of the cross-

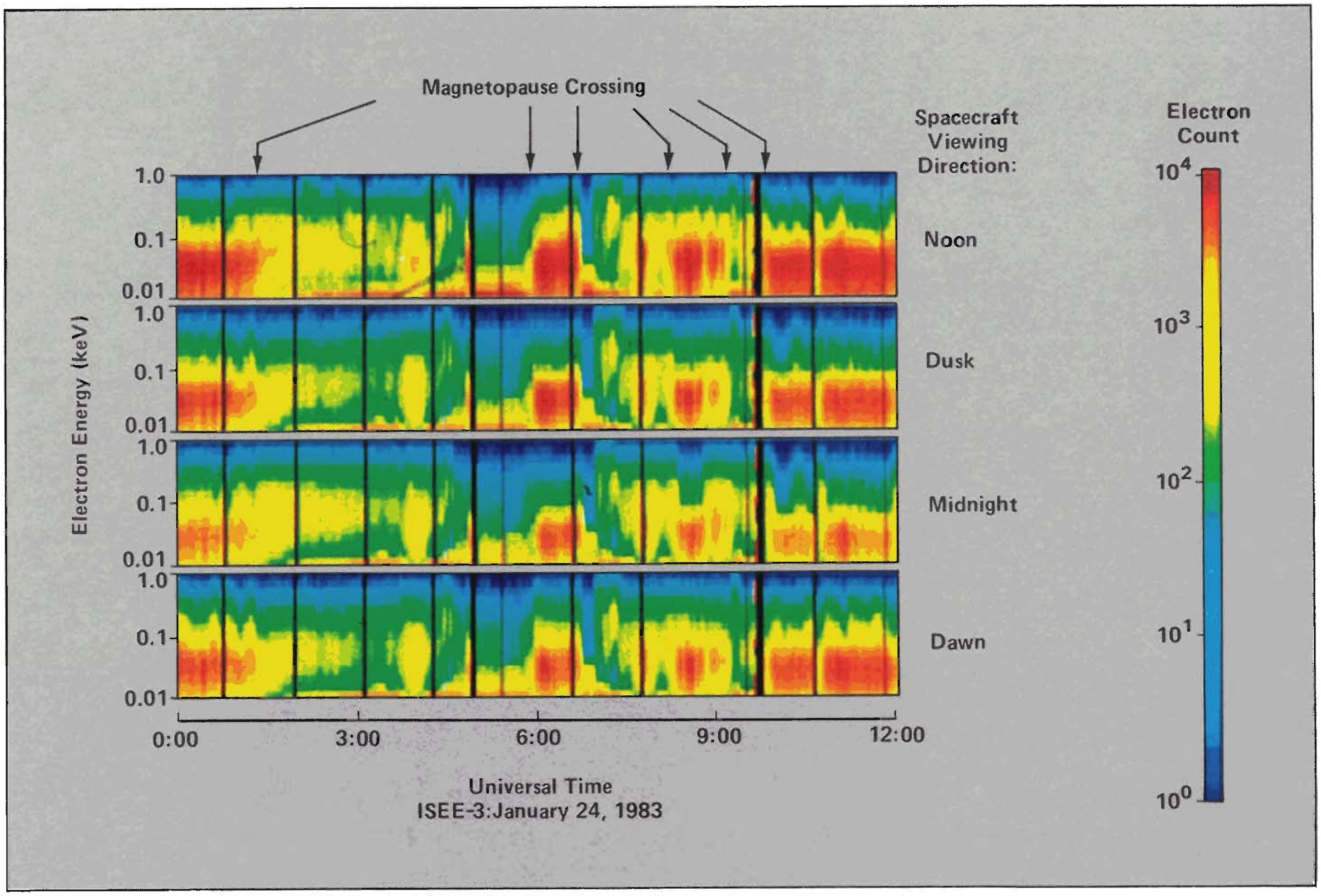


Fig. 10. Electron spectrograms from the instrument aboard ISEE-3 illustrate the variability of the plasma observed in the distant geomagnetic tail. Each panel shows an average of the energy spectra over a quadrant in the viewing direction of the spacecraft, the spectra being color coded according to the logarithm of the count rate measured by the ISEE-3 analyzer. The vertical scale for each panel is electron energy that increases logarithmically; the horizontal scale is universal time (which is based on the earth's rotation) relative to Greenwich. Color spectrograms provide an overview of the data and are used for timing different events, for selecting intervals of data for special study, and for illuminating certain aspects of the electron velocity distributions. For example, here many of the sharp changes in the spectrograms reveal frequent crossings of the magnetopause.

ings are definitely associated with auroral substorms.

Plasma Entry Into the Tail. Before we can understand the dynamic behavior of the distant magnetotail and before we can understand the effect of substorms in this region, we must try to understand the "quiet time" structure and configuration of the tail. We do this by looking at the general patterns of ISEE-3 data throughout the distant tail. Such studies help us discern where and how the energy to fuel substorms moves from the solar wind into the magnetotail. In particular, do ISEE-3 measurements confirm the idea of an open magnetosphere with plasma entry all along the magnetopause?

The data can be analyzed to yield density, temperature, and bulk flow speed of the plasma. These parameters can then be correlated with the magnitude and direction of the magnetic field as measured by the Jet Propulsion Laboratory's magnetometer aboard ISEE-3. Figure 11 shows two such sets of simultaneous plasma and magnetic field data.

In part (a) of Fig. 11 there are three crossings of the magnetopause (dashed vertical lines) characterized by dramatic changes in all three plasma parameters and marked changes in the magnetic field data. An outward crossing of the magnetopause takes the spacecraft from the plasma-poor tail lobe to an outside region with more normal flow of the solar wind. (The solar wind adjacent to and outside the magnetopause is usually called the *magnetosheath* and is separated from the undisturbed solar wind by a collisionless bow shock.) Such crossings are thus identified (as at 19:21 and 20:36 UT) by increases in the density and flow speed of the plasma as well as a drop in its temperature. The magnitude of the magnetic field drops as the spacecraft goes from the stronger terrestrial to the weaker interplanetary field lines. Further, the direction of the field rotates from the radial sun-earth direction (an azimuthal angle of about either 180 or 0 degrees, depending on whether the spacecraft is in the southern or northern lobe, and a polar angle of 0 degrees) to a direction characteristic of the interplanetary field lines (in this case, an azimuthal angle of about 100 degrees and a highly variable polar angle). Inward crossings of the magnetopause (as at 19:51 UT) have oppositely directed changes in the plasma and magnetic field data.

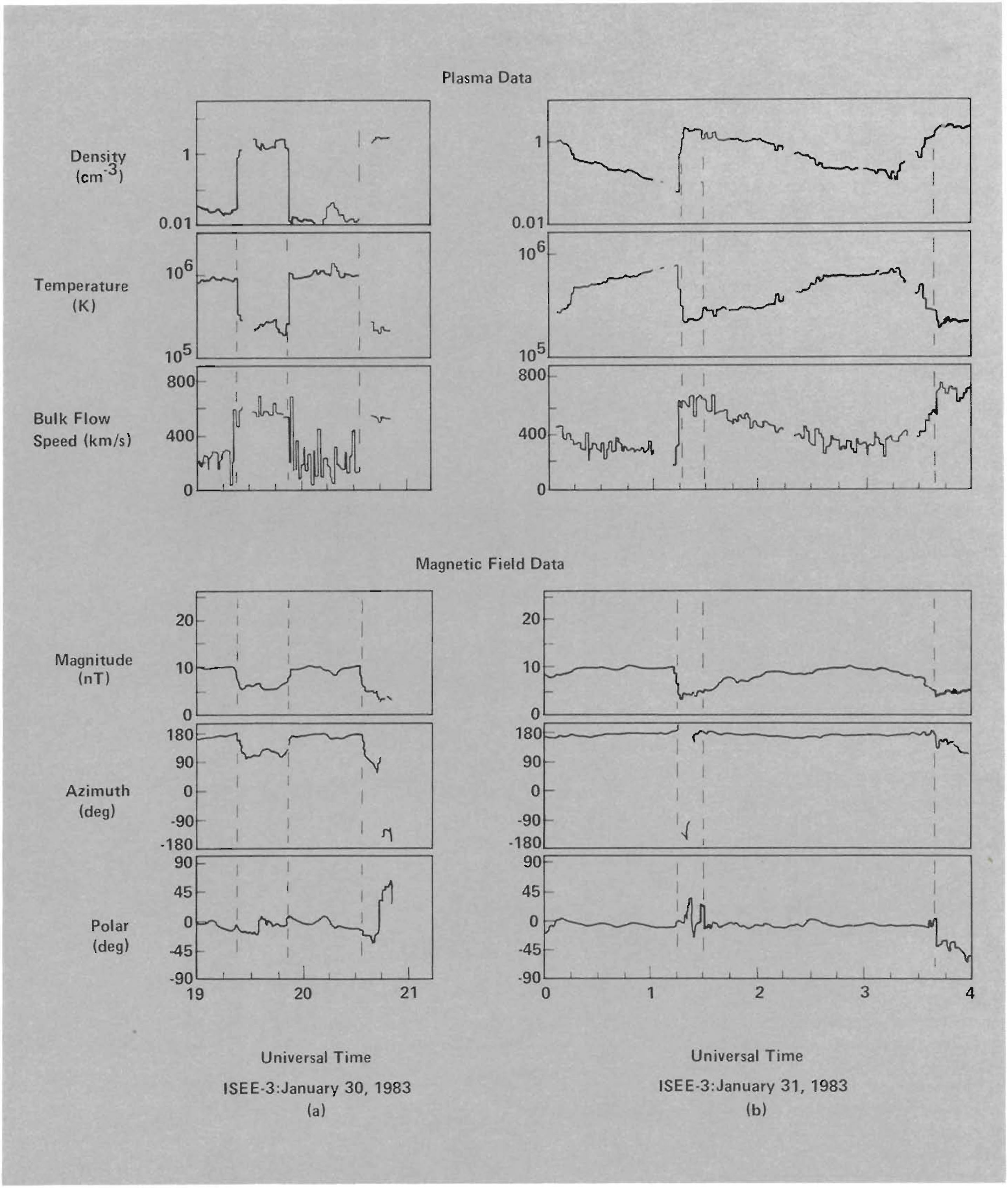


Fig. 11. Plasma and magnetic field data from ISEE-3 illustrating crossings of the magnetopause (vertical dashed lines). (a) The dramatic changes here are typical of a locally closed magnetopause as the spacecraft crosses from the plasma-depleted tail lobe to the denser, flowing, solar wind plasma outside the magnetosphere, or vice versa. (b) The more gradual changes in plasma parameters for the magnetopause crossing at 1:31 UT are typical of a locally open magnetopause in which plasma is drifting across that region of the magnetopause into the tail lobe. (The units of magnetic field magnitude are nanotesla (nT).)

The changes depicted in part (a) of Fig. 11 are what would be expected for a closed magnetosphere without local plasma entry. Frequently, however, the data are similar to those in part (b). Here the outward crossing at 1:14 UT is similar to those of part (a), but the inward crossing at 1:31 UT is quite different in that the changes in the plasma parameters are only gradual rather than dramatic. We know this is a true inward crossing because the magnetic field rotates back to the radial direction and its magnitude increases. These data show a region of plasma just inside the magnetopause that differs only slightly from the plasma outside. In fact, as the spacecraft penetrates with time deeper into the magnetosphere, the plasma gradually changes to one characteristic of the inner tail lobes, that is, with low density and flow velocity and high temperature. Thus, in this latter crossing we have detected the direct entry of solar wind plasma into the magnetosphere.

The third crossing of the magnetopause at 3:41 UT also shows a continuous change in the plasma parameters as the spacecraft crosses the surface in an outward direction, although the changes are more rapid in this case. There are two possible explanations: either the magnetotail has swept by the spacecraft more rapidly, or the region of plasma detected on the inward crossing has thinned, resulting in the more discontinuous transition from tail lobe to magnetosheath. In fact, careful examination of the crossing at 1:14 UT shows the hint of either a thin region of tailward-moving plasma or a very quick crossing of a thicker region. It is difficult to distinguish such effects using data from a single spacecraft.

We feel these data are, indeed, evidence that at times the solar wind plasma outside the magnetosphere but far down the tail flows relatively unimpeded across the magnetopause to populate the distant tail lobes. However, the plasma does not always have free entry to the lobes. Crossings that show a sudden, very large change in density (by a

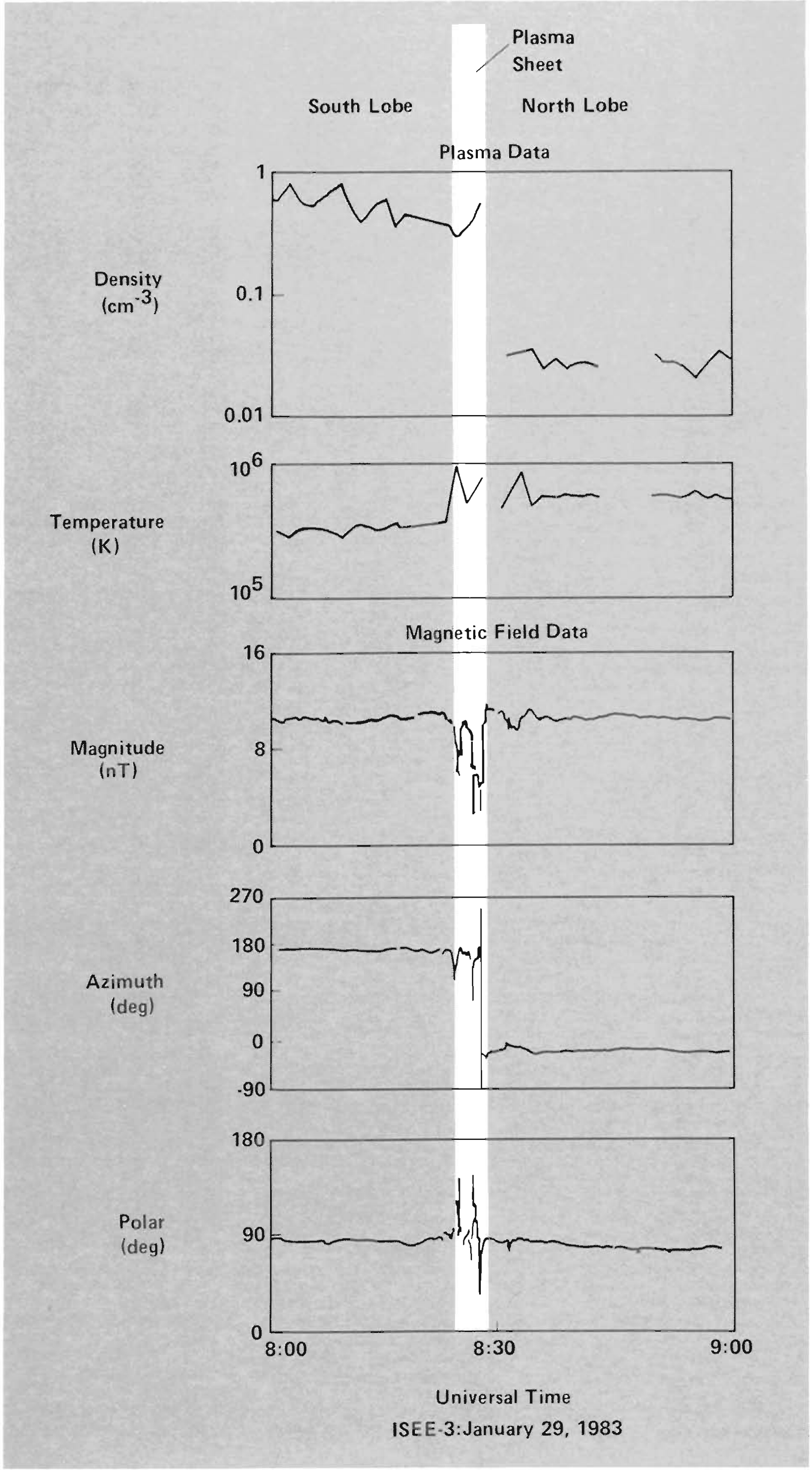


Fig. 12. These data for a traversal of the plasma sheet by ISEE-3 show a large difference between the electron densities of the north and south lobes. Such density differences are controlled by the polarity of the interplanetary magnetic field (Fig. 13) and indicate, at that point in the tail, a closed magnetopause in one lobe and an open magnetopause in the other (Fig. 14).

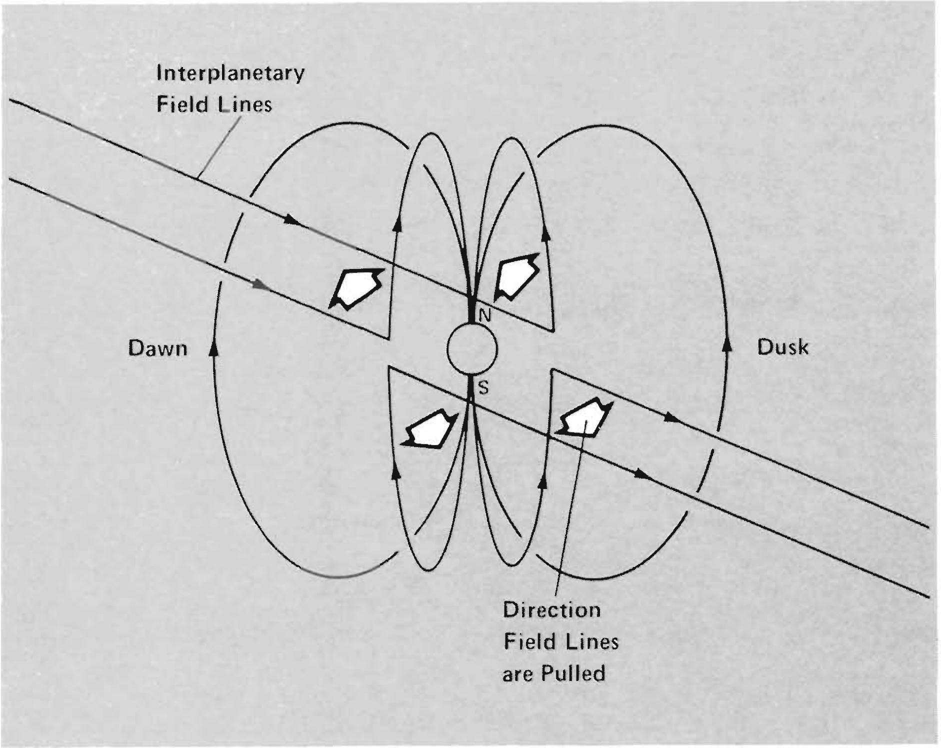


Fig. 13. Magnetic reconnection, as seen from the sun, at the dayside of the magnetosphere. The interplanetary magnetic field lines shown here have their polarity directed away from the sun, have a southward component, and are reconnecting with terrestrial field lines. The reconnected field lines are dragged back into the tail lobes in the asymmetric manner indicated by the arrows. In other words, recently reconnected field lines are pulled by field tension toward opposite sides of the magnetosphere over the northern and southern polar caps. A reversal in the polarity of the interplanetary field reverses the asymmetry of this process.

factor of 50 to 100) clearly are examples where the magnetopause is locally closed to direct penetration by solar wind plasma. We believe that plasma entry to the tail lobes is largely controlled by external factors. In fact, we have observed an asymmetry between the plasmas in the north and south tail lobes that appears to be controlled by the polarity of the interplanetary magnetic field (which changes at the earth an average of two to four times a month).

Asymmetry of Tail-Lobe Densities. Figure 12 is an example of one of the more rapid crossings of the central plasma sheet that were observed by ISEE-3. The plasma and magnetic field data extend over a 1-hour period and can be identified as a crossing from one tail lobe to the other by the reversal of magnetic field direction (the azimuthal angle switches from 180 to 0 degrees). The plasma sheet is identified by the decrease in field magnitude and the fluctuating field orientation. We can further identify this as the plasma sheet rather than plasma outside the magnetosphere by the fact that its temperature is almost ten times greater than that typical of plasma outside.

Of particular interest in Fig. 12 is the fact that the south-lobe plasma (left side) has a density comparable to that of the plasma sheet and more than ten times higher than plasma in the north lobe (right side). Comparable density differences between the two lobes have been observed whenever rapid transits of the plasma sheet occur. However, the plasma of higher density is sometimes in the south lobe, sometimes in the north lobe.

The polarity of the interplanetary magnetic field determines which lobe contains the densest plasma. We learned this from the fact that, for all rapid plasma sheet traversals examined to date, the south-lobe density was higher when the interplanetary field was directed toward the sun and lower when the field was directed away from the sun (all these events occurred when ISEE-3 was on the dawn side of the tail). Thus, the asymmetry in plasma density revealed by ISEE-3 depends on a property of the interplanetary field and thus appears to be linked with magnetic reconnection.

A natural explanation of the asymmetry lies in the corresponding asymmetry of the reconnection of field lines at the front, or dayside, of the magnetosphere. Figure 13 depicts this situation in a view of the earth as seen from the sun. Here the interplanetary field lines are shown with a southward component, the most efficient configuration for magnetic reconnection, and a westward component caused by the spiraling of field lines due to the sun's rotation (see the figure in "The Solar Wind"). For the case depicted, the field lines are directed away from the sun (which can be seen more easily in the side view of Fig. 7, illustrating the same configuration).

The tension resulting from this asymmetric reconnection of field lines (that is, the reconnection of field lines that are not truly antiparallel) is such as to pull the lines in the northern hemisphere toward the dawn side as they are dragged back into the magnetotail by the flow of the solar wind and, likewise, to pull the lines in the southern hemisphere toward the dusk side. When the interplanetary field is directed toward the sun, the manner in which the field lines get pulled back into the tail reverses. These effects lead to asymmetries along the boundaries of the geomagnetic tail and within the distant tail lobes. In particular, for the situation of Fig. 13 in which the field lines are dragged back along the northern dawn flank and the southern dusk flank, we expect, in these regions, to observe a magnetopause boundary of open field lines. Elsewhere we would expect a closed magnetopause boundary.

Asymmetric entry of plasma is the result of this asymmetric reconnection. Figure 14 represents a cross section of the distant tail as viewed from the earth when the interplanetary field is directed away from the sun. It shows entry of plasma through the open regions of the magnetopause and consequent drift toward the plasma sheet. Plasma entry occurs along the length of the tail wherever the reconnected field lines cross the magnetopause and is prevented elsewhere.

Although the northern dusk and southern dawn regions of the magnetopause are locally closed at this particular distance downtail, these regions must be open at some further distance if all lobe field lines are the result of magnetic reconnection at the nose of the magnetosphere. However, because the solar wind is continuously carrying toward the earth interplanetary field lines of varying orientation, the geometry of reconnection is always changing at the front of the magnetosphere. What we observe for a cross section relatively close to the earth are the open regions due to *recently* connected field lines that are being dragged down the tail. Those field lines that were reconnected at an earlier time produce an open magnetopause much further downstream.

This, then, is the general understanding that we have gained from ISEE-3 as to how solar wind plasma and energy enter the magnetotail. In particular, the ISEE-3 measurements have provided substantial evidence that the distant tail is open because of reconnection at the front of the magnetosphere. Now we can return to the question of how this added energy is dissipated during a substorm, and we can examine how the far magnetotail reacts as stored energy is explosively released close to the earth.

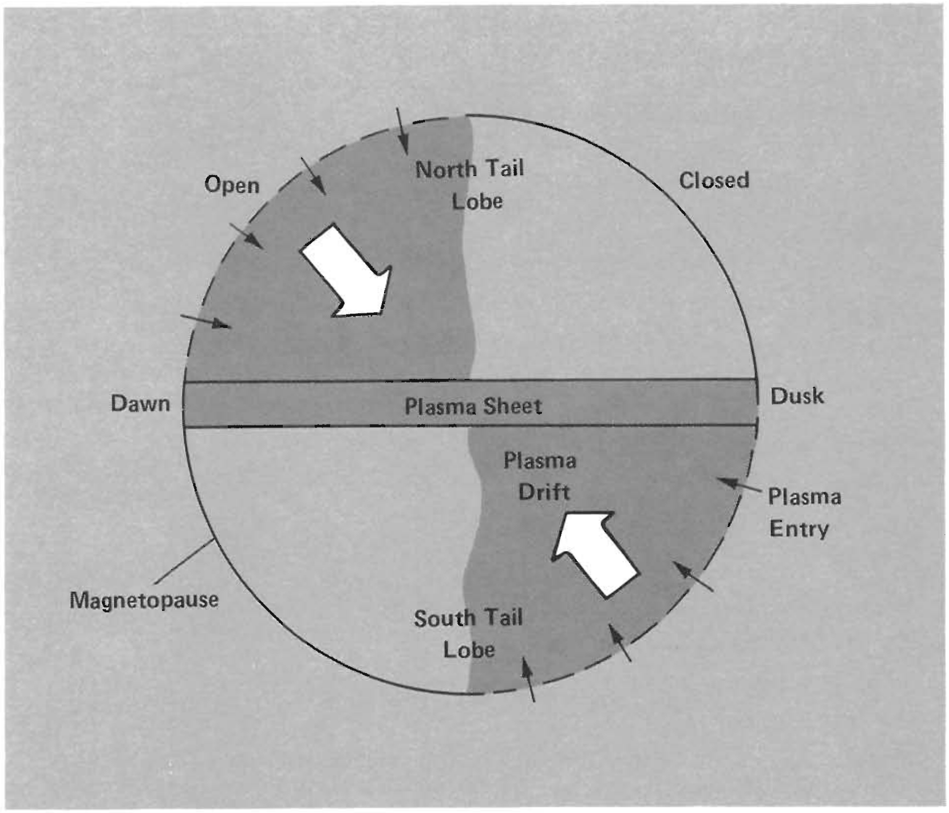


Fig. 14. Cross section of the distant geomagnetic tail as seen from the earth, illustrating the asymmetric manner in which solar wind plasma fills the tail. The open portions of the magnetopause consist of field lines that were reconnected at the front of the magnetosphere and dragged by the solar wind back into the lobes to this point in the tail. The closed portions have field lines that were reconnected earlier and whose open regions are thus much further down the tail.

Mapping a Magnetospheric Substorm

As noted earlier, substorms are believed to be initiated by magnetic reconnection within the near-earth plasma sheet. The near magnetotail can be almost continuously monitored by satellites in geosynchronous orbit 42,000 kilometers (6.6 earth radii) from the center of the earth. Scientifically, this distance is very interesting because it is at the outer edge of the Van Allen belt with its trapped radiation and is also at the inner edge of the magnetotail plasma sheet (Fig. 7). Paul Higbie and Richard Belian at Los Alamos have provided a system of energetic-particle sensors, called the Charged Particle Analyzer (CPA), for an entire series of geosynchronous satellites. The system monitors (for both the U.S. Departments of Energy and Defense) aspects of the near-earth environment, including a variety of magnetospheric conditions. In particular, some of the data can be used to map a magnetospheric substorm by comparing CPA data taken close to earth with simultaneous measurements by ISEE-3 in the deep magnetotail.

The Growth Phase. Data from geosynchronous satellites show that magnetic field and plasma parameters undergo a very regular and predictable sequence of variation in association with substorms. Whenever the flow of the solar wind and the orientation of the interplanetary field cause an enhanced coupling between the solar wind and the magnetosphere, magnetic field lines at geosynchronous orbit begin stretching, going from a dipole-like configuration to a stressed, tail-like configuration. This tail-like field is indicative of enhanced cross-tail currents and, thus, of increased storage of magnetic energy in the tail lobes and plasma sheet. (In effect, the plasma sheet is flattened by in-

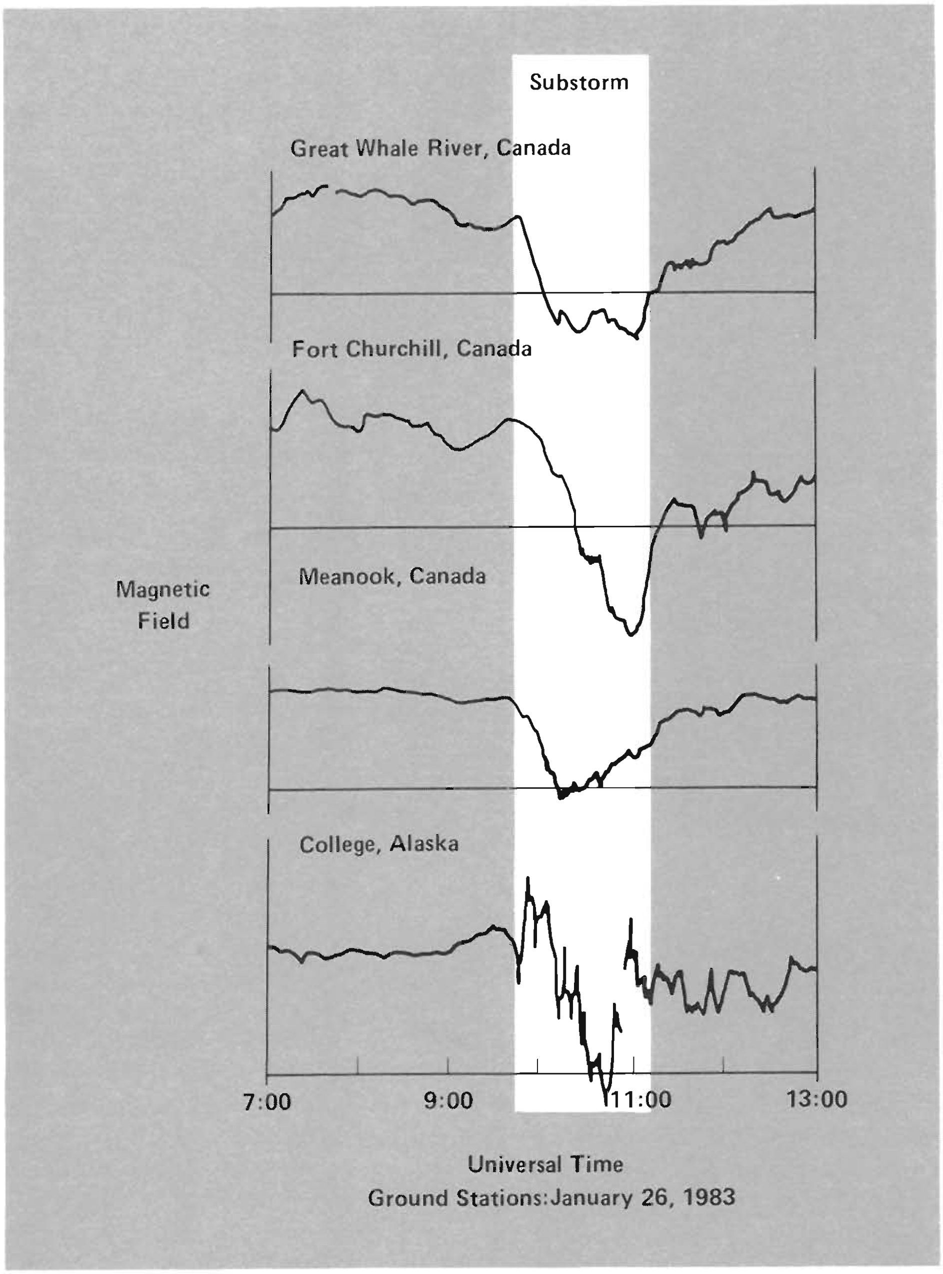


Fig. 15. Magnetic signature of an auroral substorm recorded at different ground stations on January 26, 1983. These widely separated magnetometer stations began recording, almost simultaneously at 9:45 UT, the classic "negative-bay" signature indicative of strong ionospheric current flow. The disturbance persisted for more than an hour, and the magnetic field then gradually returned to its pre-substorm values. Figures 16 and 17, respectively, show data collected during this same substorm by a satellite in geosynchronous orbit and by ISEE-3 in the distant tail.

creased magnetic pressure from the tail lobes.) This stored energy is eventually dissipated during substorms, and the interval of energy storage is known as the *growth phase* of the substorm.

Near midnight at geosynchronous orbit the growth phase has a clear signature—a change in the spatial distribution of energetic plasma particles. In particular, electrons with energies of 10 to 100 keV progressively change from being concentrated perpendicular to the local magnetic field lines to being concentrated along field lines. This change is due to plasma drift in the distorted, tail-like magnetic field and occurs about a half to two hours before the substorm release of energy.

Substorm Onset. Within a minute or so of the start of the substorm, the stressed magnetic field configuration snaps rapidly back to a more dipole-like configuration. At this time hot plasma and energetic particles are injected into the region of geosynchronous orbit. The injected plasma appears to be related directly to the rapid conversion of stored magnetic energy into plasma flow energy at reconnection sites in a limited segment of the plasma sheet. Further, the higher energy particles appear to be accelerated very impulsively, probably because of intense induced electric fields in the region where the magnetic field lines are merging.

One result of this activity in the tail is auroral activity of the kind discussed previously that produces strong magnetic perturbations near the northern and southern poles of the earth. These field disturbances are the electromagnetic signatures of strong currents flowing in the polar ionosphere, and they always accompany the visual auroral displays. Figure 15 shows the classic "negative-bay" signature of a substorm beginning more or less simultaneously at a series of magnetometer stations at about 9:50 UT on January 26, 1983. The fact that these ground sites are separated by thousands of kilometers gives us an indication that the

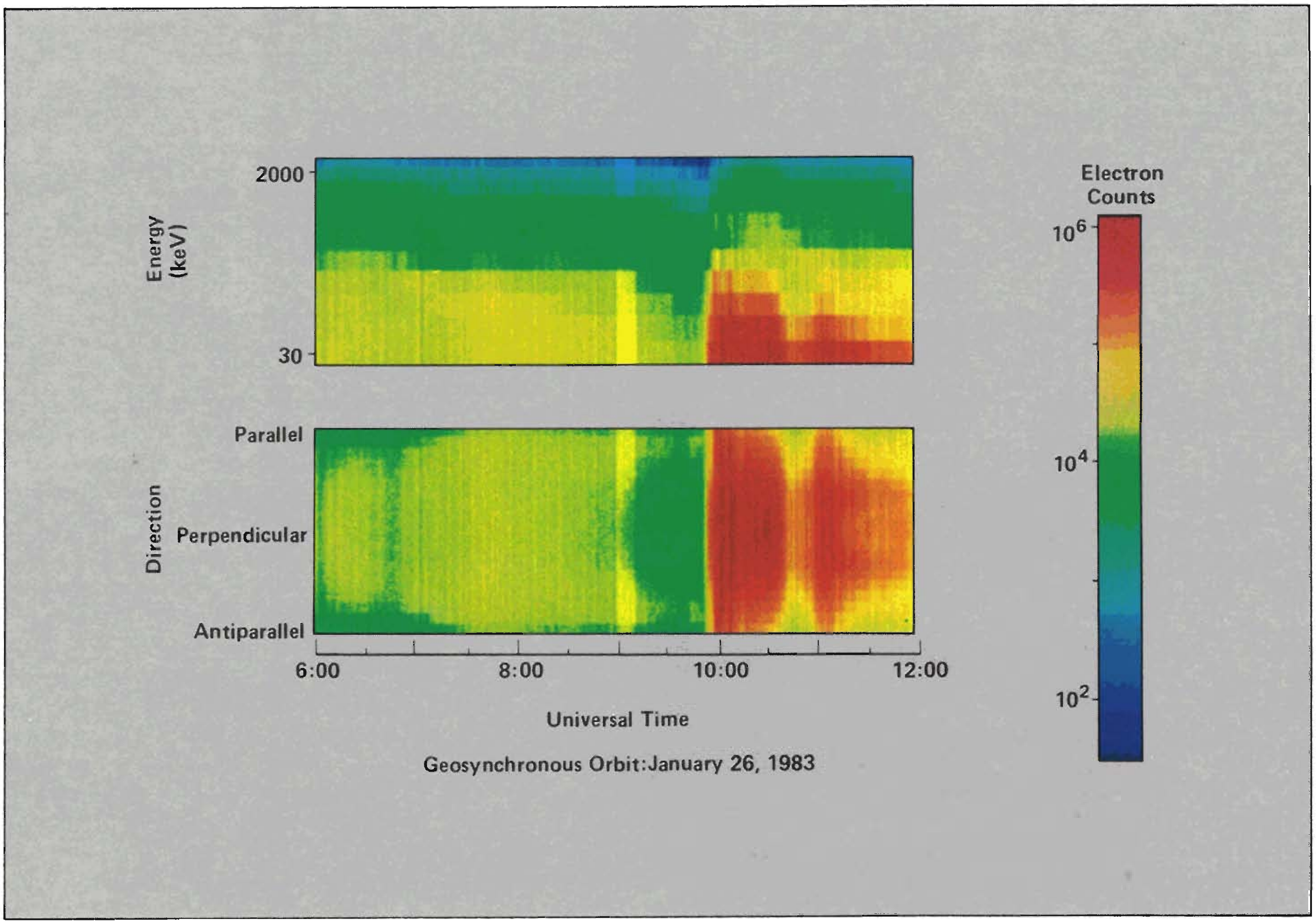


Fig. 16. Electron spectrograms, from a satellite in geosynchronous orbit, for the substorm of January 26, 1983. These panels give the energies and direction of highly energetic electrons encountered by a satellite located near the midnight meridian and 6.6 earth radii from the center of the earth. Note the distinctive "fork" in the lower spectrogram beginning around 8:55 UT. This change in electron motion from perpendicular to parallel to the field is indicative of the growth phase of the substorm. The sharp change at 9:50 UT signals the onset of the substorm itself.

substorm effects may be truly global. The magnetic records are relatively calm until substorm onset, then show large negative deflections that persist for about an hour, and finally return to pre-substorm values.

Near-Earth and Deep-Tail Comparisons. The particular substorm of Fig. 15 was observed both by satellites in geosynchronous orbit and by ISEE-3. First we will examine energy-time and angle-time spectrograms for the geosynchronous data. The two panels of Fig. 16 show the energetic (30 to 2000 keV) electron data from a satellite in geosynchronous orbit near the midnight meridian. The upper panel shows only those particles that are moving perpendicular to the local field. The lower panel gives the direction of motion of the energetic electrons, ranging from antiparallel (bottom) through perpendicular (center) to parallel (top) with respect to the local magnetic field lines.

We see from these panels that at around 8:55 UT the energetic electrons at geosynchronous orbit became largely field aligned. This is especially evident in the second panel where the number of electrons moving

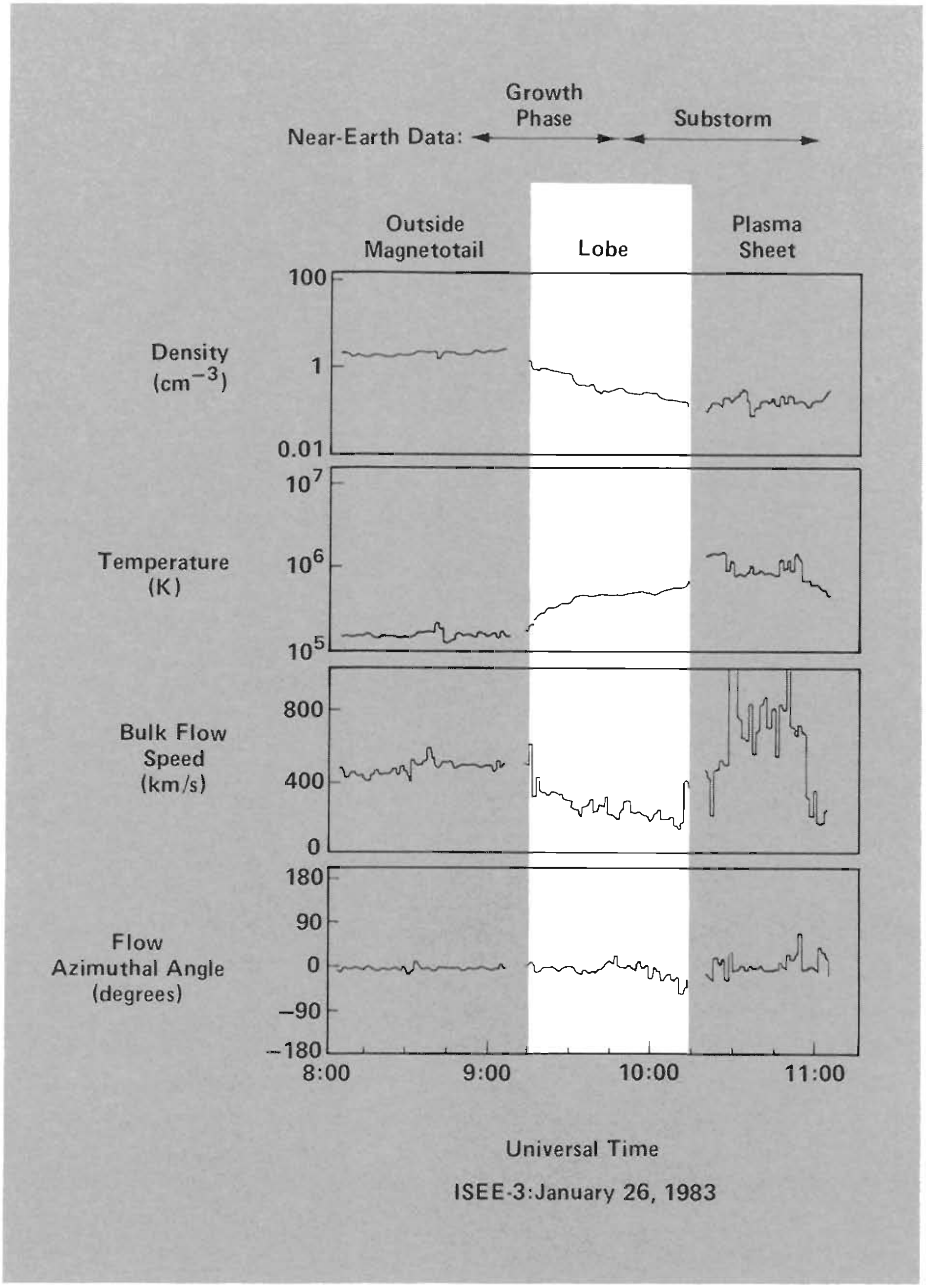


Fig. 17. ISEE-3 data from the distant tail for the substorm of January 26, 1983. Comparison of the near-earth data (arrows at top) with the ISEE-3 data shows that, at about 20 minutes after the start of the growth phase close to the earth, ISEE-3 crossed from outside the magnetotail into one of the tail lobes. Then, about 20 minutes after the onset of the substorm, the spacecraft entered the plasma sheet and encountered very high tailward plasma flows.

perpendicular to the field (center of the panel) drops, whereas the number of those moving along the field lines (top and bottom of the panel) increases. Such behavior is indicative of the growth phase of the substorm.

At 9:50 UT, when the ground stations were picking up the signature of the onset of a magnetic disturbance, the motion of the energetic electrons switches from field aligned to field perpendicular and their number increases dramatically. At this point energetic electrons are being injected from the "accelerator" in the magnetotail into the atmosphere.

What did ISEE-3 detect far down the tail at this time? Figure 17 shows that the spacecraft was outside the magnetotail (in the magnetosheath) for over an hour, but at 9:15 UT it crossed the magnetopause into the south tail lobe. This transition occurred about twenty minutes after the start of the growth phase of the substorm close to earth. At 10:11 UT, ISEE-3 encountered the plasma sheet with its high temperatures and very strong flow of plasma tailward. This latter crossing occurred about twenty minutes after the start of the actual magnetic disturbance near the earth. Thus, there is a close systematic relationship between the development of the substorm close to earth and ISEE-3 plasma observations twenty minutes later. But what changes took place in the magnetotail to cause these boundary crossings?

Growth-Phase Model. Between January 24 and February 8, 1983, we identified approximately 75 substorms at geosynchronous orbit. In about half of these cases, the geosynchronous satellites were in the proper position (near midnight) to see the growth phase. For most (about 30) of these latter, well-characterized substorms, ISEE-3 detected a corresponding transition from outside the magnetotail into one of the lobes. This pattern is so regular we feel that not only does the magnetotail expand during the growth phase but that the entire tail from geosynchronous orbit outward participates in that expansion (Fig. 18).

These results have led us to model the growth phase as follows. A southward turning of the interplanetary field lines enhances the rate at which magnetic reconnection occurs on the dayside of the magnetosphere. As these newly connected lines are dragged into the tail, magnetic and plasma energy are added at an enhanced rate, and the tail grows in diameter. During our late January and early February observations, ISEE-3 was positioned in an almost stationary fashion outside the distant magnetotail surface so that growth of the tail would eventually cause it to envelop the spacecraft. Simple calculations show that during a substorm growth phase we should expect the magnetotail to increase in diameter by several earth radii. Our observations with ISEE-3 are a strong confirmation of this heretofore speculative idea.

Substorm Model. The results of Fig. 17 also demonstrate another feature frequently found in our data, namely the envelopment of ISEE-3 by the plasma sheet. This occurs about twenty or thirty minutes after the start of a magnetic disturbance at the earth. The event of January 26, 1983 is typical in that the envelopment includes strong tailward jetting of plasma (between 10:20 and 11:00 UT the bulk plasma flow velocity was regularly greater than 700 kilometers per second). Further, for numerous examples the data recorded by ISEE-3 show the spacecraft passing from one lobe into the plasma sheet and then back into the same lobe again as if a bulge in the plasma sheet had passed by.

We believe such behavior is the signature of plasma release in the manner depicted in Fig. 19. The plasma sheet is severed close to earth, flows tailward as a plasmoid, and reaches ISEE-3 about twenty or thirty minutes later. The delay in arrival is consistent with the bulk flow speeds measured for the plasma of about 500 to 1000 kilometers per second. The plasmoid's dimensions increase substantially as it departs because it is moving through regions of decreasing magnetic pressure. The large size of the plasmoid results in a bulge in the magnetopause that travels along with it.

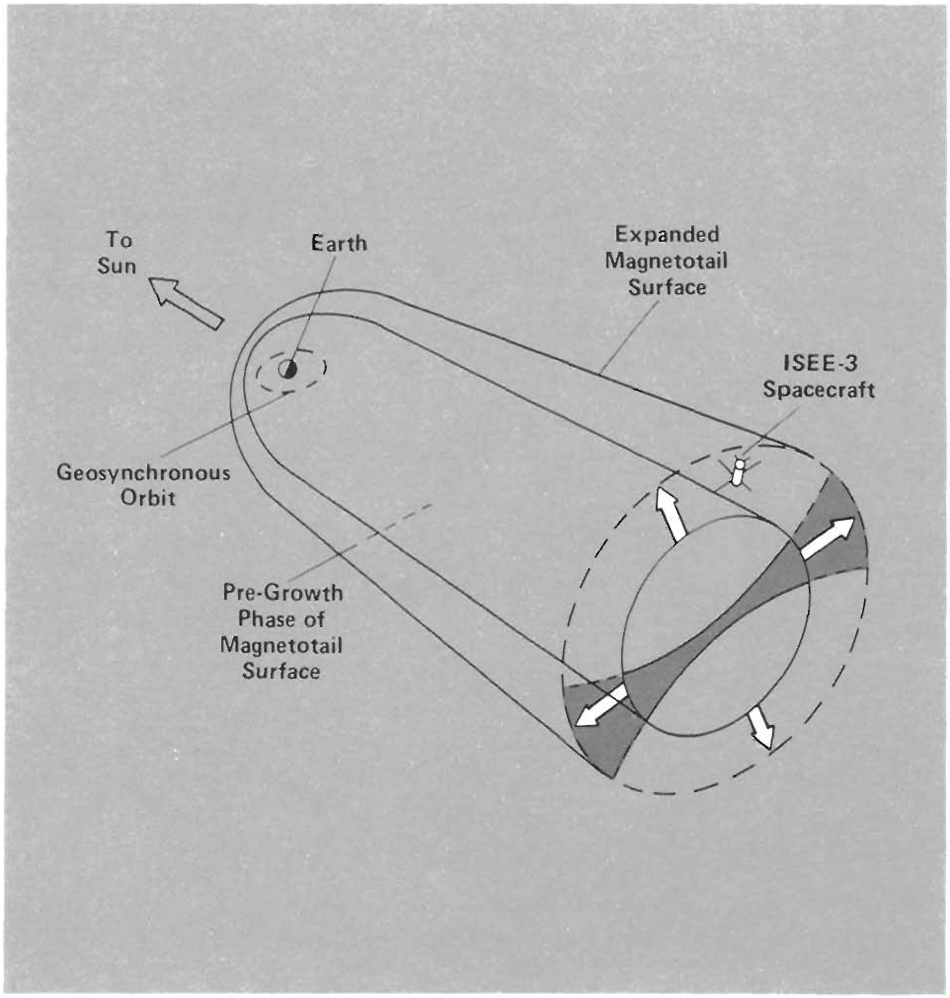


Fig. 18. Growth-phase model. Before the growth phase of a substorm begins, the magnetotail is relatively small in cross section, and, quite often, ISEE-3 resides outside. As plasma and energy are added to the tail, the cross section apparently grows until ISEE-3 is enveloped. The data show this as an inward transition from outside the magnetosphere to one of the tail lobes. Such lateral growth of the tail is seen all the way from geosynchronous orbit (6.6 earth radii) to more than 200 earth radii down the tail.

ISEE-3 provided two other pieces of information that strongly support the plasmoid model as the correct interpretation of the substorm-related encounters with the plasma sheet. First, during these encounters the magnetic field in the newly expanded plasma

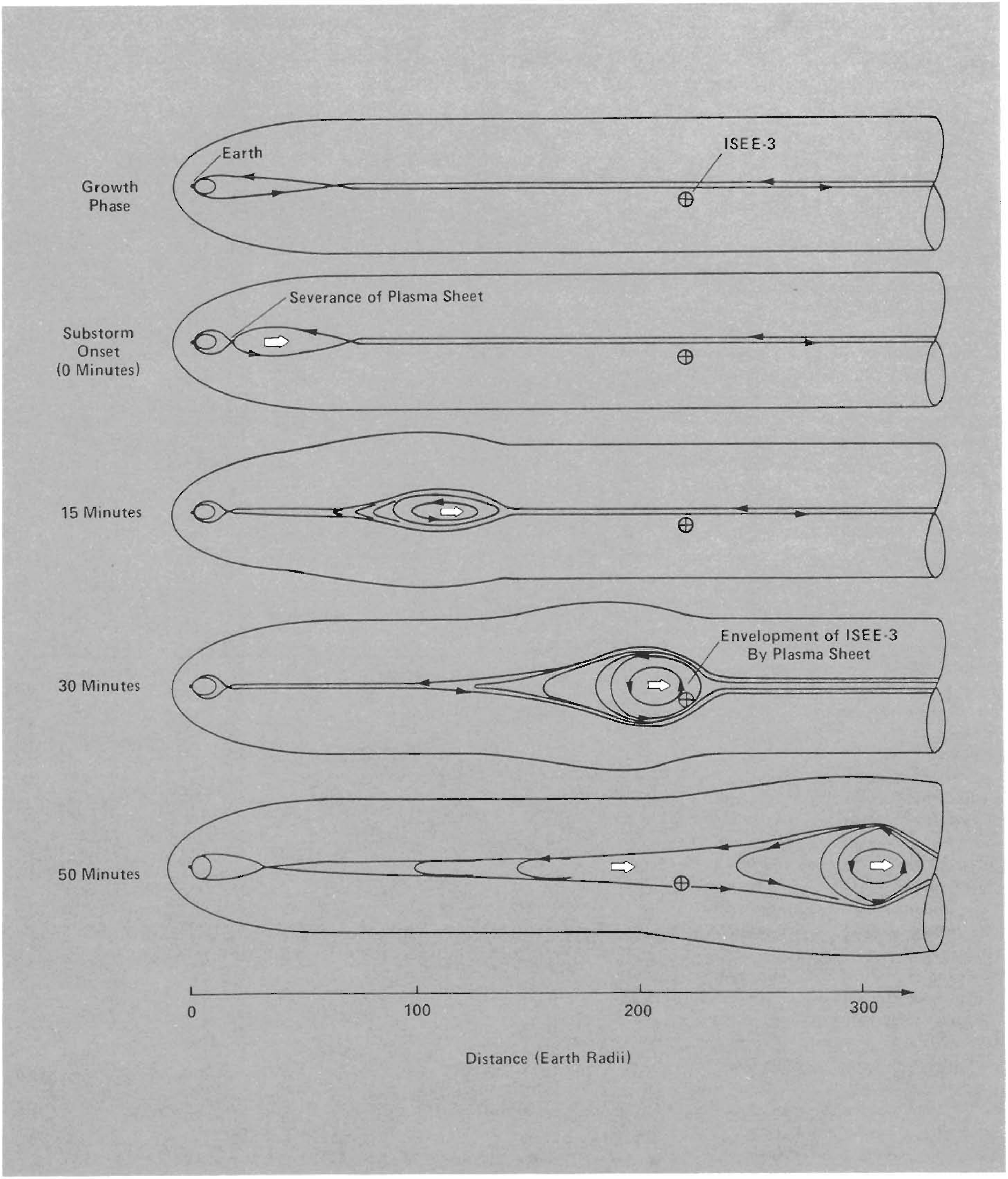


Fig. 19. Substorm model. After plasma and energy have built up in the magnetotail during the growth phase, a portion of the plasma sheet is severed by reconnection close to earth, causing substorm onset. The plasmoid thus formed hurtles down the tail, eventually enveloping ISEE-3 about thirty minutes later at its vantage point nearly 1,400,000 kilometers from earth. The envelopment is seen by instruments in the spacecraft as a transition into the plasma sheet. (White arrows indicate plasma flow; black arrows indicate the direction of the magnetic field.) This model is supported further by data such as those shown in Figs. 20 and 21.

sheet usually points steeply northward for a few minutes, then points southward (often steeply) for a longer period of time. For example, Fig. 20 shows the envelopment of ISEE-3 by the plasma sheet about 30 minutes after the onset of a substorm at the earth on January 25, 1983. This envelopment is indicated by the decreased magnetic field strength and high plasma bulk flow speed between about 5:30 and 6:10 UT, but we also see that the polar angle of the magnetic field turns steeply northward (positive 45 degrees) for several minutes followed by an even steeper and longer southward turning for most of the remaining period of the plasma sheet encounter. Examination of Fig. 19 shows that this is the expected magnetic signature of a passing plasmoid: at the front of the plasmoid the field lines point northward, just past its center they reverse and point southward, and toward the back they gradually resume a more radial direction.

Data from another particle experiment on ISEE-3 on the flow direction for energetic electrons (about 100 keV) give further support of the model. For example, in Fig. 21 we see for an event on February 16, 1983, that energetic electrons appeared at 3:05 UT, a few minutes before the plasma sheet enveloped the spacecraft, and these electrons were almost all streaming tailward. About 12 minutes later (20 minutes after the onset of a substorm near the earth) ISEE-3 encountered the plasma sheet, and, at the same time, the electron distribution became isotropic.

This change in the flow direction of energetic electrons is typical of many observed events and can be explained with the help of Fig. 19. As the plasmoid approaches ISEE-3 the spacecraft will first encounter "interplanetary field lines," that is, lobe field lines that reconnected near the earth after the plasmoid departed. These field lines pass around the outer part of the plasmoid and are contracting behind it, helping to pull it out along the tail. Electrons, accelerated at the near-earth neutral line, flow freely along these field lines and into the solar wind

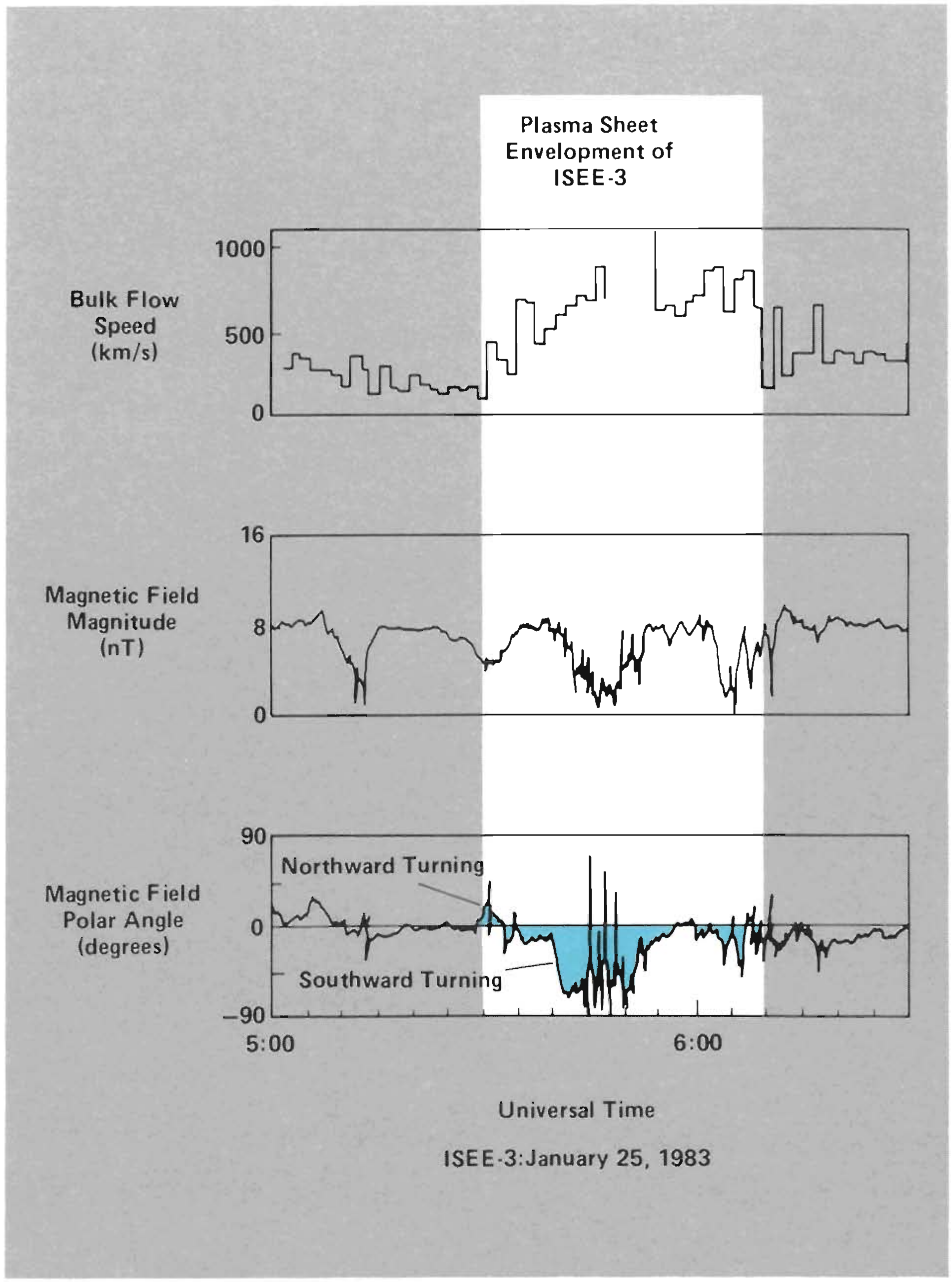


Fig. 20. Data from ISEE-3 illustrating the turning of the magnetic field for a substorm-related encounter with the plasma sheet. The plasma bulk flow speed and the magnetic field magnitude show that ISEE-3 was enveloped by the plasma sheet from 5:30 to 6:10 UT on January 25, 1983. The data for the polar angle of the field show a steep northward turning for several minutes followed by a longer southward turning as predicted in Fig. 19 for the envelopment of the spacecraft by a moving plasmoid.

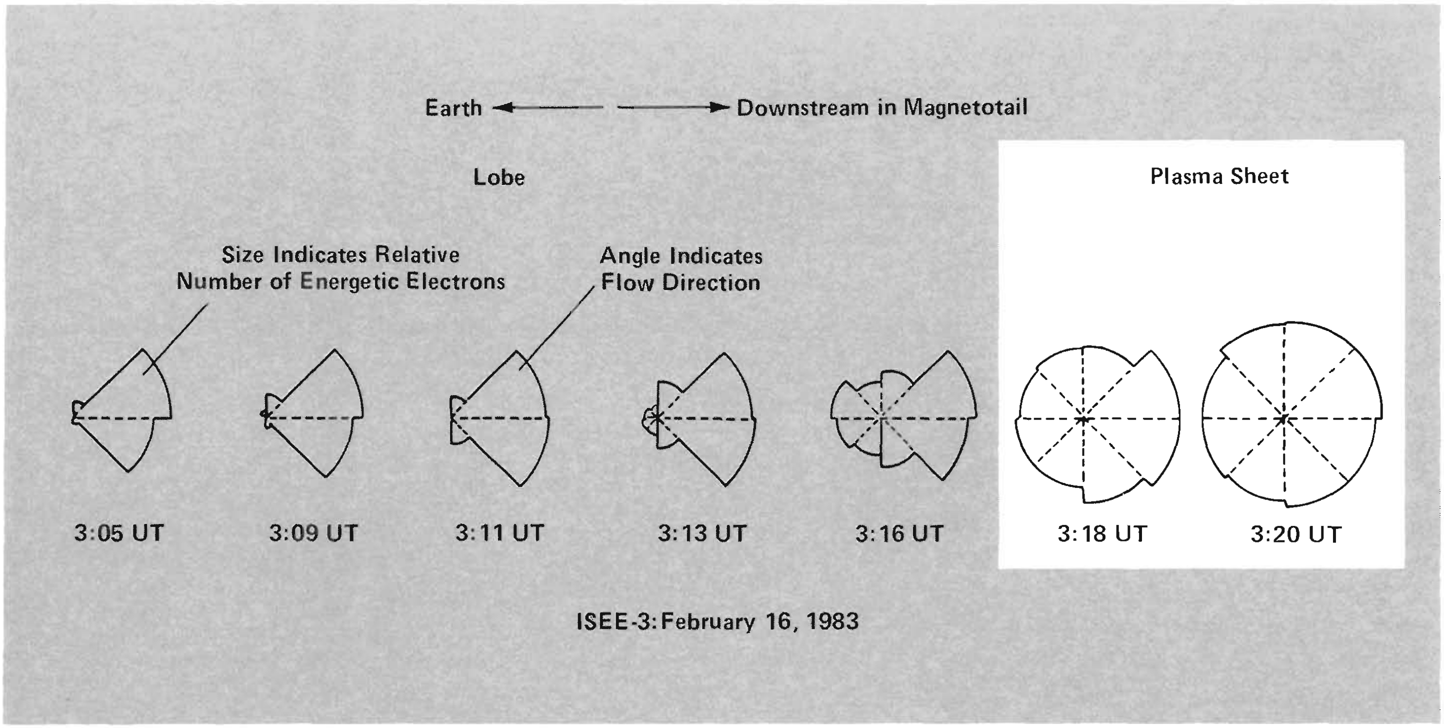


Fig. 21. Electron angular-distribution data from ISEE-3 for a substorm-related encounter with the plasma sheet. The azimuthal orientation of the motion of energetic electrons (about 100 keV) is shown. The area of each sector is proportional to the relative electron count and the orientation of that sector indicates the flow direction (for example, sectors pointing to the right are proportional to the number of electrons flowing down the tail away from the earth). For several minutes before ISEE-3 was enveloped by the plasma sheet on February 16, 1983, electron flow was strongly tailward. When the spacecraft entered the plasma sheet, motion of the electrons became isotropic. These data agree with the model that explains the plasma sheet encounter as the envelopment of ISEE-3 by a moving plasmoid. (Adapted from a paper presented by M. Scholer of the Max Planck Institut für Extraterrestrische Physik in Garching bei München.)

without reflection, thus their unidirectionality. Inside the plasmoid, ISEE-3 encounters closed magnetic loops containing electrons trapped there when the plasma sheet was severed. These electrons have isotropic motion because they have bounced back and forth within the plasmoid.

What happens when ISEE-3 is within the tail but too far above or below the plasma sheet to be enveloped by the plasmoid as it sweeps by? Because the plasmoid creates a moving bulge in the magnetotail, there should be a moderate north-then-south deflection in field direction and a temporary compression of the lobe field. Indeed, such magnetic signatures, called traveling compression regions, are seen frequently.

Thus, ISEE-3 has confirmed, in a remarkably graphic way, the ideas about substorms and their significance for magnetospheric energy gain and loss that were correctly inferred but only dimly seen in earlier near-earth observations. Continued study of the data acquired by the spacecraft during several passes through the distant tail will provide important new insights into the complicated physics of magnetic reconnection.

In the meantime, the busy spacecraft has been flung once more by the moon into an orbit that should allow it to intercept the tail of a comet (see "Comet Exploration and Beyond"). Although there are many differences between them, the geomagnetic tail and a comet's tail both result from interactions with the passing solar wind. The chance to use the same ISEE-3 instruments to measure directly the plasmas and fields within both entities should help us understand many of the similarities and differences in the mechanisms of tail formation in these remarkable solar system objects. ■

Comet Exploration and Beyond

On December 22, 1983, the ISEE-3 spacecraft whipped by the moon and headed off on a new orbit designed to intercept the Giacobini-Zinner comet in late 1985 (see figure). After having completed this maneuver by passing just seventy miles above the moon's surface, the spacecraft was renamed ICE (for International Cometary Explorer) and its mission was switched from an exploration of the earth's magnetotail to an exploration of the local environment of a comet.

Comets are formed under conditions totally different from those that lead to the planets of our solar system. They appear to consist principally of ice mixed with dust, though cold chemistry within them has also produced more complex molecules such as methane, ammonia, and cyanogen.

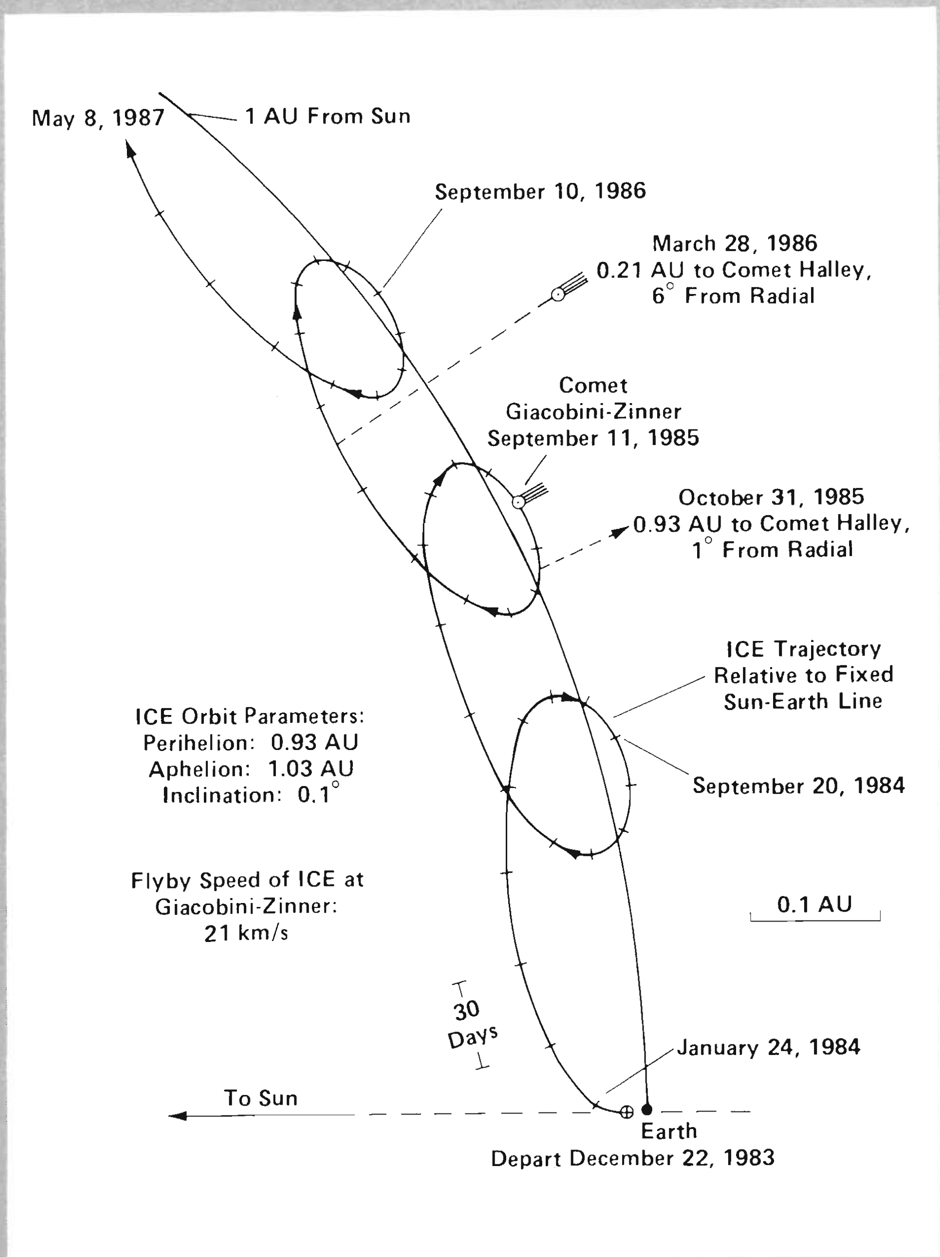
Giacobini-Zinner is an old, relatively small comet that passes by the earth approximately every thirteen years. The comet's glowing head of gases and dust blowing off its core reaches a visible size of 50,000 kilometers (intermediate in size between the earth and Jupiter) and then tapers into a tail that stretches out nearly 800,000 kilometers. Like other comets, Giacobini-Zinner is believed to have been formed in the vast reaches of space beyond Pluto and then pulled into our solar system by gravity. It has been observed since 1900, trapped in a circuit between the sun and the orbit of Jupiter.

The comet will be met by ICE within 70.8 million kilometers of earth. Because its orbit is known to vary as much as half a million kilometers from one solar passage to the next, astronomers will be working to pin down its precise orbit. At the time of intersection (September 11, 1985), the spacecraft hopefully will pass through the comet's tail within about 3000 kilometers of its head.

The likelihood of encountering dust from the comet's core in this close approach may result in damage to the spacecraft instruments. However, the danger is expected to be minimal since the earth has moved across Giacobini-Zinner's debris path several times in the past and encountered spectacular meteor showers, but with relatively short path lengths indicating small particle size for the dust.

As ICE moves through the tail, its instruments will provide the first *in situ* measurements of a comet and its environment. We hope to measure the nature and rate of ionized-gas release and learn how the comet's head and tail are affected by the solar wind. Two questions of particular interest are whether a bow shock forms upstream in the solar wind and whether the solar wind interaction accounts for the mysteriously high rate at which ionized material spews from a comet. The loss rate is known to be ten times higher than can be explained by evaporation due to solar radiation. It will also be interesting to search for magnetic reconnection in the tail.

The passage of Giacobini-Zinner in September 1985 will be followed only a few months later by Halley's comet. Observations of both comets will offer an un-



Trajectory of the ICE spacecraft after its lunar boost (bottom) on December 22, 1983. Here the line from earth to sun has been fixed in space, and we see that the relative motion of the spacecraft takes it around the sun with a radius of about one astronomical unit (AU), but in a manner that causes it to spiral ever further from earth. ICE will cross through the tail of the Giacobini-Zinner comet on September 11, 1985 and will make observations of Halley's comet from upstream positions in the solar wind around October 31, 1985 and March 28, 1986.

paralleled opportunity to compare two quite different visitors from interstellar space. Halley's comet is younger, larger, and moving faster than Giacobini-Zinner. As it passes the earth every seventy-six years, the size of its head becomes nearly as large as Jupiter, and its tail stretches 100 million kilometers. Significant differences between the two comets are expected in composition, structure, and their interaction with the solar wind.

To study Halley's comet, Russia, the European Space Agency, and Japan will launch a fleet of probes ahead of its path. Five spacecraft will make visible and ultraviolet images of the comet's sunlit core, measure the dust it throws off, and detect any bow shock the comet may create in ramming its way through the solar wind.

ICE will also make measurements near Halley's comet by moving to two positions upstream of the comet after leaving Giacobini-Zinner (see figure). The first position (October 31, 1985) will place the spacecraft 138.4 million kilometers from the comet and 76 million kilometers from the earth; the second (March 28, 1986) will place it 35 million kilometers from the comet and 96.5 million kilometers from the earth. From both upstream positions ICE will collect data on the solar wind a day or so before the plasma reaches the comet. The effect of this measured solar wind on the comet will then be observed both by the international probes close to the comet and by telescopes on the earth.

This spacecraft's exploration of the magnetotail and two comets will conclude in 1987, almost a year after its final observation of Halley's comet. Though it will continue measuring the interplanetary solar wind, the spacecraft by this time will be 121 million kilometers from earth. At this point radio signals from its low-gain antennas, originally designed for use only to a distance of 1.6 million kilometers, will be growing too weak to be detected. ICE will return to near-earth orbit in 2015 as gravity pulls it around the sun-earth system. ■

AUTHORS

John T. Gosling received his Ph.D. in physics from the University of California, Berkeley in 1965, having completed a thesis on the emission of x rays from the auroras. On a postdoctoral appointment at the Laboratory and then, starting in 1967, at the High Altitude Observatory in Boulder, Colorado, he did some of the first research on the solar wind as well as helping to photograph the solar corona outside an eclipse with an experiment flown on NASA's Skylab. He returned to Los Alamos in 1975 to work on a variety of topics in space plasma physics including solar mass ejections, the origin and evolution of disturbances in the solar wind, and magnetic reconnection at the earth's magnetopause. Recently, using data from plasma experiments flown on a variety of space probes and collaborating with numerous colleagues from around the world, he has dealt with ion dissipation and acceleration at collisionless shocks and with plasma entry into the geomagnetic tail. Gosling has just finished a term as associate editor of the space physics volume of the *Journal of Geophysical Research.*

Daniel N. Baker, head of the Space Plasma Physics Group of the Earth and Space Sciences Division, has been at Los Alamos since 1977. Prior to this he was a graduate student at the University of Iowa and a Research Fellow at the California Institute of Technology and was involved with the interpretation, analysis, and modeling of space plasma data. His research includes a variety of experimental and theoretical work on energetic plasma phenomena ranging from spacecraft instrument design to an analysis of Voyager data in the upstream region of Jupiter to the theoretical modeling of the development of magnetotail instabilities. Since coming to Los Alamos, Baker has devoted much of his effort to understanding substorms in the magnetosphere, and he has shown how these disturbances contribute to anomalies in the operation of near-earth spacecraft. At present he is interested in using modern computer techniques to enhance the acquisition, dissemination, and display of spacecraft data. He is now serving on several NASA advisory committees as well as the National Academy of Sciences Space Science Board Committee on Solar and Space Physics.

Edward W. Hones, Jr., received his Ph.D. in physics from Duke University in 1952. After working seven years in nuclear reactor physics with E. I. DuPont de Nemours and Co., he became interested in space research, which he pursued at the Convair Corporation in San Diego, the Institute for Defense Analyses in Washington, D.C., the University of Iowa, and, beginning in 1965, Los Alamos. He pioneered the observation and interpretation of plasma flow in the magnetosphere and, using a long sequence of satellite observations, developed new, compelling evidence in 1976 and 1977 that substorms involved magnetic reconnection and the formation of plasmoids. Thus he was particularly happy when he found, in the ISEE-3 observations described in this article, the rapidly departing plasmoids that he had predicted six years earlier.

AUTHORS

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Further Reading

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